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ENERGETICS AND SYSTEMS MODELING: A FRAMEWORK STUDY FOR ENERGY EVALUATION OF ALTERNATIVE TRANSPORTATION MODES

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KINGMAN BUILDING
FORT BELVOIR, VIRGINIA 22060

DECEMBER 1977 IWR CONTRACT REPORT 77-10

ENERGETICS AND SYSTEMS MODELING: A FRAMEWORK STUDY FOR ENERGY EVALUATION OF ALTERNATIVE TRANSPORTATION MODES

A Report Submitted to the:

U.S. Army Engineer Institute for Water Resources
Kingman Building
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Under

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Report compares economic and energetic approaches for evaluating transportation systems. Discusses general energy theory, methods for calculating the energy value of goods and services, energy flows associated with natural systems, and energy benefit/cost analysis as applied to alternative modes for transportation of bulk commodities. Direct and indirect energy costs of transporting coal, or its energy equivalent, are evaluated, with energy costs per ton-mile and energy yield ratios (i.e., units of energy transported per unit of energy cost) compared for barge, slurry pipeline, railroad and

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electric transmission line systems.

PREFACE

The following contract report is one of several products resulting from research and studies into energetics which were sponsored over the past three years by the U.S. Army Corps of Engineers, Institute for Water Resources[1]. The report presents the results of research conducted by Bayley, et. al, Engineering and Industrial Experiment Station, University of Florida, in Gainesville. The objective of this research was to compare economic and energetic approaches for evaluating transportation systems. In addition to discussing general energy theory, methods for calculating the energy value of goods and services, and energy flows associated with natural systems, the report compares energy benefit-cost analysis as applied to alternative modes for the transportation of bulk commodities. The direct and indirect energy costs of transporting coal, or its energy equivalent, are evaluated with energy costs per ton-mile and energy yield ratios (i.e., units of energy transported per unit of energy cost) compared for barge, slurry pipeline, railroad, and electric transmission line systems.

[1]Other research products consist of: (1) a contractor's draft research report entitled, "A Comparison of Energetics and Economic Benefit-Cost Analysis for the Upper St. Johns River," Bayley, et. al, June 1976, and (2) A summary report entitled "Energetics: Systems Analysis with Application to Water Resources Planning and Decision-Making," Caldwell D. Meyers, December 1977. The latter report, also prepared under contract, reviews the scientific concepts underlining energetics and evaluates their potential application in water resource planning and decision-making. It is available as IWR Contract Report No. 77-6.

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SUMMARY

This report presents a comparison of economic and energetic approaches for evaluating transportation systems. Many of the basic energetic concepts presented in section II-A were developed by Dr. Howard T. Odum at the University of Florida and further developed for transport systems in this report. In the Introduction, section I, a general discussion of economics and energetics is presented to point out similarities, differences, advantages, and disadvantages of the two approaches. The discussion of general energy theory, section II-A, discusses the laws of energetics, the method of comparing different types of energy flow through the concept of energy quality, and the relationship between energy and economic value. Methods for calculating the energy value of goods and services, the role of energy flows of natural systems in a regional or transportation system, and spatial energy theory for determining the competitiveness of different fuel source locations are also presented. In particular, economic benefit-cost analysis as applied to transportation systems by the Corps of Engineers is compared to a comparable energy benefit cost analysis.

In order to illustrate the methodology of energetics, several transportation systems were analyzed in order to calculate the energy cost of each. Both direct fuel energies for operation, indirect energy requirements for goods and services, and energy flows associated with natural systems were considered. Some attempt was made to measure the disruption of natural systems by an existing or planned transport system. Since this report was not directed towards a particular problem or project, natural system disruption was only considered in a general way with ecological models presented for proposed research. Approximate analyses were made for barge transportation, railroad transportation, slurry pipelines, and electrical transmission lines. In particular, the direct and indirect energy costs of transporting coal were evaluated. Energy costs per ton-mile and energy yield ratios (energy transported ÷ energy costs) are presented. Several analyses of the direct and indirect energies associated with building barges, towboats, and locks and dams are also presented.

In order to show how energetics might be used at a regional scale of evaluation, the problem of coal development and transportation in the Northern Great Plains is presented in section V. Model development, mathematical analysis, computer simulation, and energy concepts are presented in this analysis for the purpose of illustrating energy systems modeling at a regional scale. However, this analysis is primitive and is presented only to show the basic

type of approach. The results are not considered final nor is the model considered adequate enough to define the role of transportation in a region. The methodology and energy concepts presented in this report could serve as a framework for conducting a detailed analysis of fossil fuel resource locations and associated transportation links for establishing a national energy plan.

CHAPTER I
INTRODUCTION

The purpose of this report was to develop a methodology based on the application of energetic concepts, principles, and system techniques to the problem of evaluating transportation systems. Energetic evaluation and system formulation as used here refers to much of the work of Howard T. Odum (1971, 1976) at the University of Florida and other investigators who have used energy formulations and concepts for characterizing the systems of both man and nature. These concepts can be extended to benefit/cost analysis where benefits and costs can be expressed in units of energy flow. Environmental destruction can then be included as an energy cost by evaluating the natural productivity lost. An energy benefit/cost analysis as an alternative to economic cost/benefit analysis is discussed in section II-B. Thus, the use of the word energy in this report does not only refer to fossil fuels or electricity.

In general, there are three aspects of transportation systems which should be evaluated. First, there are the indirect environmental and energy costs associated with goods required for capital investment, replacement, and operation. Second, there are the direct fuel and labor costs for operation of the system and the direct natural energy losses due to construction and operation of the system. Third, there are the induced effects caused by a transportation system in a given region (e.g., a highway resulting in residential growth). In order to show how these effects can be evaluated with energetic methodology, the transport of coal by barges, railroads, and pipelines were studied. In addition, the conversion of coal to electricity and its transmission over high voltage lines were also considered. Wherever data permitted, the indirect and direct energy costs of these systems were evaluated. Attempts were also made to evaluate natural system costs, but this was difficult due to the general nature of this report and the scarcity of ecological field work. Because of the lack of energy accounting data, energy flows are approximated in many instances from a dollar flow and a corresponding energy/dollar ratio. If society kept account of energy as it does money this approximation would not be necessary.

In order to illustrate how energetic-ecological modelling can be used to show the role of transportation at a regional level, a model of the interaction between coal development, transportation systems, and regional development for the Northern Great Plains is presented in section IV. This model is intended as an example to show model development, simulation, and energetic principles. A much more detailed approach including data accumulation is needed to accurately model this region.

Planning Process

The planning process used by the Corps of Engineers is a complex iterative process consisting of economic and environmental inventories, identification of needs, statement of planning objectives, development and testing of alternatives which meet objectives, benefit/cost analysis techniques, environmental quality considerations, and measures of social well-being. An attempt is made to optimize the overall objectives, and part of this for transportation planning is to maximize the net economic benefits associated with a given project. An energetics approach would also consider objectives, needs, and testing of alternatives but would try to assign energetic value to the natural and human systems affected by a given project. A project objective might be to pick that project which maximized the total energy flow (including fossil fuel and natural). In particular, the net energy benefits could be calculated by comparing a system to its next cheapest alternative in terms of energy cost (both indirect and direct fossil fuels and natural energy losses) and calculating the energy savings. This energy could then be used for the creation of economic value somewhere else in the economy. This process is explained more fully in section II-B.

General Discussion of Economic, Ecologic and Energetic Concepts

Many of the concepts of energetics as presented in this report developed out of the study of ecosystems (Odum, 1971). Concepts and principles which described the behavior, functioning, and organization of natural systems emerged from this work and have been used as a guide for the understanding of human systems and the interconnection of human systems and natural ecosystems. For example, the recognition that energy is the main driving force of natural systems and that ecosystems tend to adapt to external energy sources in order to maximize their total power flow led to the conception of human society as strictly dependent on, and adapting to, sources of natural energies and fossil fuels (Odum, 1973). The economic notion of maximizing the production of goods and the creation of demand seem to be related to the notion of maximizing energy flows. Economics had traditionally ignored the externalities which manifest themselves in the disruption of natural systems although there are attempts now to place economic value on natural systems (Krutilla and Fisher, 1975). However, these valuations usually deal only with the recreational benefit, i.e., the demand for the enjoyment of this resource. Energetics, on the other hand, places a value on the total work (from energy flows) that a natural system is performing. This attempt to evaluate the total contribution of natural systems is not limited to the price that man is willing to pay for a natural resource at a given time; it is a holistic approach in that it tries to evaluate the total contribution to the combined system of man and nature. The recognition that natural systems perform useful work allows evaluations of natural energy contributions to the system of man. This natural energy flow is in addition to the energy flow derived from fossil fuels. By using energy as a common denominator, one can evaluate, compare, and perhaps predict the work contributions of both natural ecosystems and man-dominated systems.

Economics is a field which has had 200 years of development while energetics as applied to the understanding of human systems is perhaps less than a decade old. Economics is concerned with the production and distribution of goods among people and has developed intricate methods for assessing the forces of supply and demand. Economics as a discipline does not usually deal with such concepts as energy as the ultimate limiting factor, biological and ecosystem degradation due to growth, and considerations of the carrying capacity of a region or the world.

However, there are similar outlooks between the two fields. The phenomena of inflation can be looked at from an energetics point of view by considering the ratio of GNP to the energy consumed (Kylstra, 1974). If the money supply relative to the total energy consumption (work done) increases, then this will be a factor in creating inflation. This is similar to the monetarist's view of inflation. The notion in economics that net national product (NNP) = (GNP - depreciation) is similar to ecological theory that net primary production = (gross primary production - respiration). The law of diminishing marginal physical returns, which says that as the amount of a variable input is increased, a point is reached beyond which marginal product declines, is similar to the limiting factor concept in ecology, e.g., the application of more and more phosphorus on a plant does not result in more and more growth. The prediction of the consumption function or demand in economics is related to the amount of disposable income. Similarly, energetics could predict demand by predicting energy available to consumers since this is a measure of their income (Hannon, 1975). It is also of interest to note that many of the formulations of Keynesian economics are in terms of stocks and flows, similar to the model formulations presented in this report (Samuelson, 1973; Wonnacott, 1974).

The notion of value is a topic which has long plagued philosophers. In economics it develops out of a pragmatic sense of what is available (supply) and what is desired (demand). An economist would assign more value to those things for which people are willing to pay more. Economics as we know it has developed in an era of abundant and available supplies of material and energy resources with a consequent development of accelerated growth and values attuned to a growth system. What will happen when fossil fuels become limiting? Since industrialized society is so intimately dependent in innumerable ways on energy, energy as a limiting factor will be of critical importance. In fact, all energy flows connected with a good may serve as an indication of the value of that good, just as the total economic cost of making a particular material is used to represent the value of that material. Using energy as the measurement of value we can determine the total energy costs of our various capital goods, their maintenance, and the proposed rate of growth of our society. This has broad policy implications since energy is one of our most critical limiting resources.

A concept widely used in ecology which may have application to economics is the theory of ecosystem development. Some ecosystem studies have shown that natural systems pass a succession from a early, high growth phase to a mature, climax net growth phase (E.P. Odum, 1971). An example of this is an old field filled with various weeds which grows gradually into a dense forest over a period of 50-100 years. The old field and early forest stages have very rapid growth rates with high yields while the older forest has a lower net growth and very low yields. This last stage is called a mature or climax stage. If it can be determined that human systems follow a similar development, then planning can be instituted for an anticipated climax or slower growth phase of society. A summary of some of the approaches of energetics and economics is contained in Table 1.

Whether energy is in short supply or not, it is of interest to minimize the energy costs of transportation in order to free energy for the production of other useful work and economic value. The energy costs of transportation include direct fuel for operation and indirect costs associated with goods, labor, and natural systems (see section II-A). Economic or dollar flows may not reflect the true costs of transportation because of market imperfections, regulation, monopoly control, and exclusion of environmental costs. This report outlines a methodology for assessing direct and indirect energy costs with several cases of transportation analyzed as examples. Unfortunately, in many cases energy costs must be calculated from dollar flows and corresponding energy to dollar ratios. More extensive funds and research would allow tracking of actual energy flows throughout the economy.

Table 1

Comparison of Economics and Energetics

Category	Economics	Energetics
Age	Fairly old and well developed	Just beginning
Measures of natural system value	Limited; uses mainly recreational benefits	Uses total work performed by natural systems by measuring their energy flows
Integration of natural and human systems	Has no common basis of value	Uses energy as a common basis of value. Notions of investment ratio for measuring development (section II-A)
Measurement of human needs and wants	Uses notions of supply and demand	Human society adapts to external availability of energy
Societal development	Concept of factor substitution leads to unlimited growth possibilities	Concept of succession in natural systems and consideration of carrying capacity leads to limits to growth
Model formulations	Stocks and flows	Stocks and flows
Maximization priniciples	Maximization of profit; maximization of economic production	Maximization of the energy flows of both man and nature subject to external constraints
Size limitations	Diminishing marginal returns	Limiting factor concept
Inflationary indicators	Size of money supply (monetarist's)	Consideration of energy to dollar ratio for economy
Measurement of real costs	Correct for market distortions and manipulations	Account for all direct and indirect energy costs, both fossil fuels and natural

CHAPTER II
DESCRIPTION OF APPROACHES

A. General Energy Theory

Energy Language

Many of the concepts presented in this reprot are illustrated with the use of a symbolic language developed by H.T. Odum (1971), the symbols of which are shown in Fig. 1. This symbolic language (and others) is an excellent way for organizing a system study, identifying major components and flows, and stimulating questions for further consideration. A systems diagram can be translated into mathematical equations since a differential equation can be written for each storage which stipulates that the time rate of change of a storage is equal to its inputs minus its outputs. Some simple examples to illustrate the language are presented in the following paragraphs and in Fig. 2.

Consider Fig. 1 for the moment. This language is useful for problems which are amenable to formulation in terms of flows and storages. Most of the symbols are explained in the legend, but the self-maintaining module (Fig. 1g) and plant population (Fig. 1h) need further explanation. Each of these will contain an assortment of storages, flows, and interaction symbols to represent the various processes that may be occuring in the plant or in the self-maintaining system. These symbols are shorthand representations of these more complicated systems.

Fig. 2 gives some simple examples of how differential equations are derived from the symbolic diagram. In Fig. 2a the storage Q is feeding back a flow, K_2IQ, to capture energy from the source I while a depreciation, K_3Q, is draining the storage. The rate of change of the storage is equal to inputs minus outputs. Fig. 2d shows a digital function in the form of a switch which senses the value of Q_2. If Q_2 is above a certain threshold value the switch closes and the flow K_1I_1 occurs. Otherwise, the switch opens and no flow occurs. An example of equations derived from a realistic model and simulation procedures is given in section IV.

Laws of Energetics

The first and second laws of thermodynamics are well known from physics and are useful for understanding the flows of energy in human societies and natural ecosystems. The first law dictates that energy cannot be created or destroyed but can only be transformed from one form to another. The second law requires that any energy flowing in a process must have part of its energy degraded to a lower quality, the disorder of the environment increasing in the process. In other words, for a system without an external energy source, the energy of that system available to perform work will decrease with every process. (Work means energy directed towards system survival).

Figure 1. The Symbols of the Energy Circuit Language Used in This Report (Odum, 1971, 1972).

a. Outside source of energy supply to the system controlled from outside; a forcing function (E).

b. Constant flow source from outside:
$J_2 - k_2J_0X/(k_r+k_1X)$, $J_r = k_rJ_0$, $J_1 = k_1XJ_0$.

c. A pathway whose flow is proportional to the quantity in the storage or source upstream ($J = k_1E$). The heat sink represents the energy losses associated with friction and backforces along pathways of energy flow.

d. Storage of some quantity in the system. The rate of change equals inflows minus outflows ($\dot{Q} = J-kQ$).

e. Interaction of two flows to produce an outflow which is some function of these flows; usually a multiplicative output, i.e., $f(X,Y) = kXY$.

f. Transactor symbol for which money flows in one direction and energy or matter in the other direction with price (P) adjusting one flow (J_1) in proportion to the other, J_2 ($J_1 = PJ_2$).

g. A combination of "active storage" and a "multiplier" by which potential energy stored in one or more sites in a subsystem is fed back to do work on the successful processing and work of that unit; autocatalytic.

h. Production and regeneration module (P-R) formed by combining a cycling receptor module, a self-maintaining module which it feeds, and a feedback loop which controls the inflow process by multiplicative and limiting actions, e.g., the green plant.

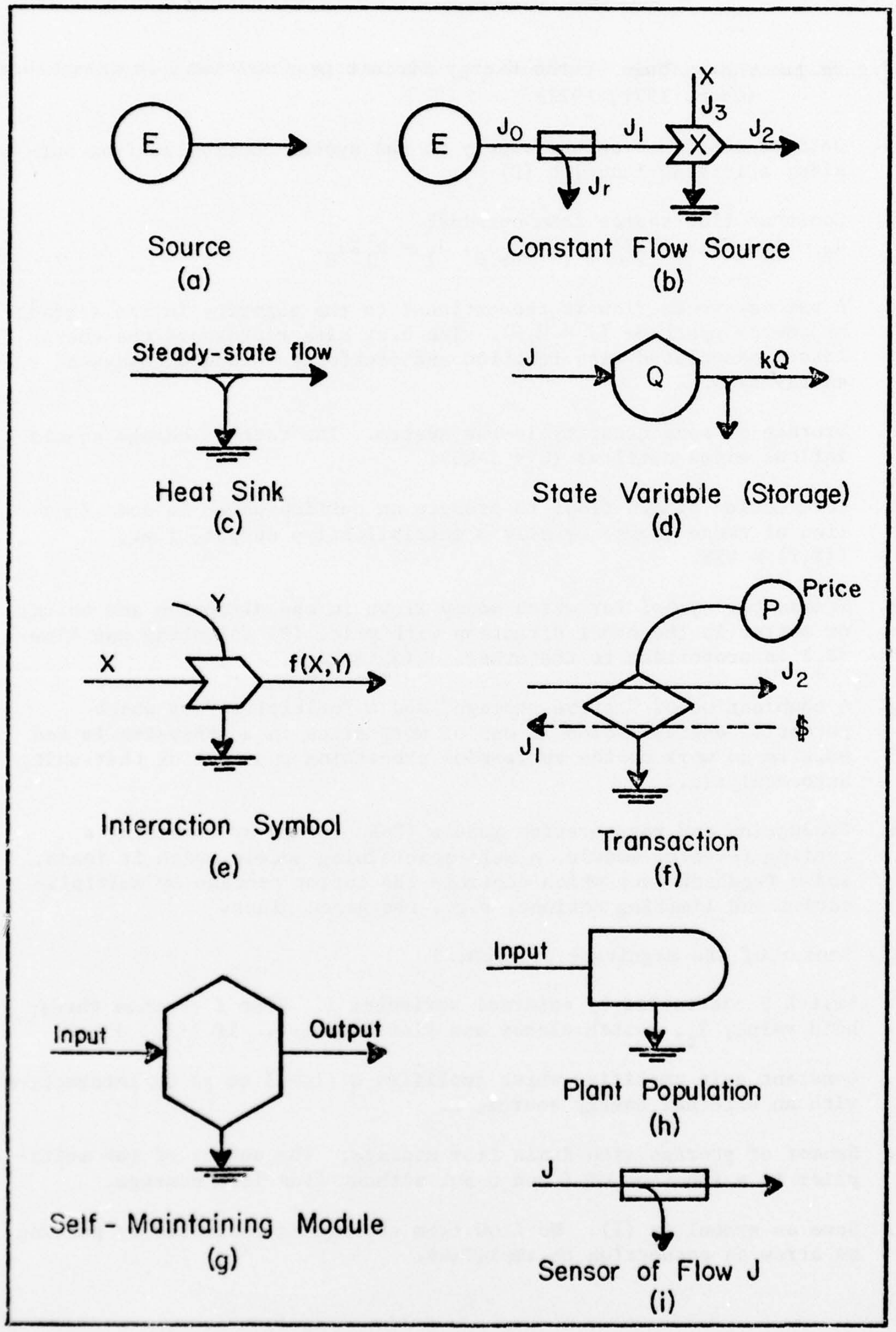
i. Sensor of the magnitude of flow, J.

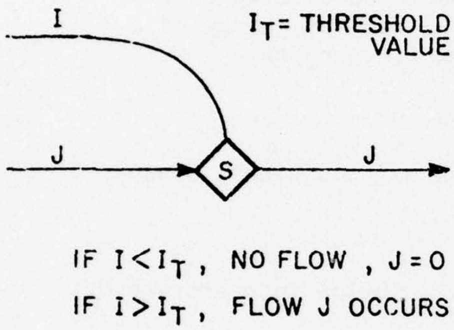
j. Switch S controlled by external variable, I. When I reaches threshold value, I_t, switch closes and flow J occurs. If $I<I_T$, $J = 0$.

k. Constant gain amplifier which amplifies a flow J to gJ by interaction with an external energy source, I.

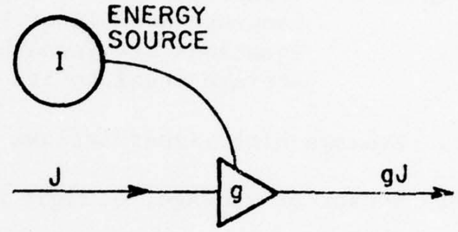
l. Sensor of storage with drain from storage. The output of the multiplier is a function of I and Q but without flow from storage.

m. Same as symbol in (l). No flow from storage is indicated by putting no arrow on connection to amplifier.

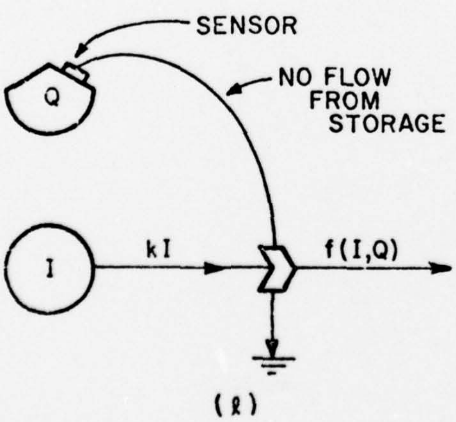

E
Source
(a)
E
J_0
J_1
X
J_3
X
J_2
J_r
Constant Flow Source
(b)
Steady-state flow
Heat Sink
(c)
J
Q
kQ
State Variable (Storage)
(d)
Y
X
f(X,Y)
Interaction Symbol
(e)
P
Price
J_2
$
J_1
Transaction
(f)
Input
Output
Self - Maintaining Module
(g)
Input
Plant Population
(h)
J
Sensor of Flow J
(i)


I
I_T= THRESHOLD VALUE
J
S
J
IF $I < I_T$, NO FLOW, J = 0
IF $I > I_T$, FLOW J OCCURS

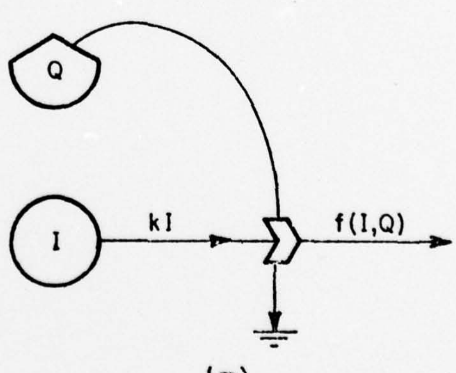
(j)


ENERGY SOURCE
I
J
g
gJ

(k)


SENSOR
Q
NO FLOW FROM STORAGE
I
kI
f(I,Q)

(ℓ)


Q
I
kI
f(I,Q)

(m)

Figure 2. Examples Illustrating the Interconnection of the Energy Language Symbols of Fig. 1. Associated differential equations are found by setting the rate of change of a storage equal to its inputs minus its outputs.

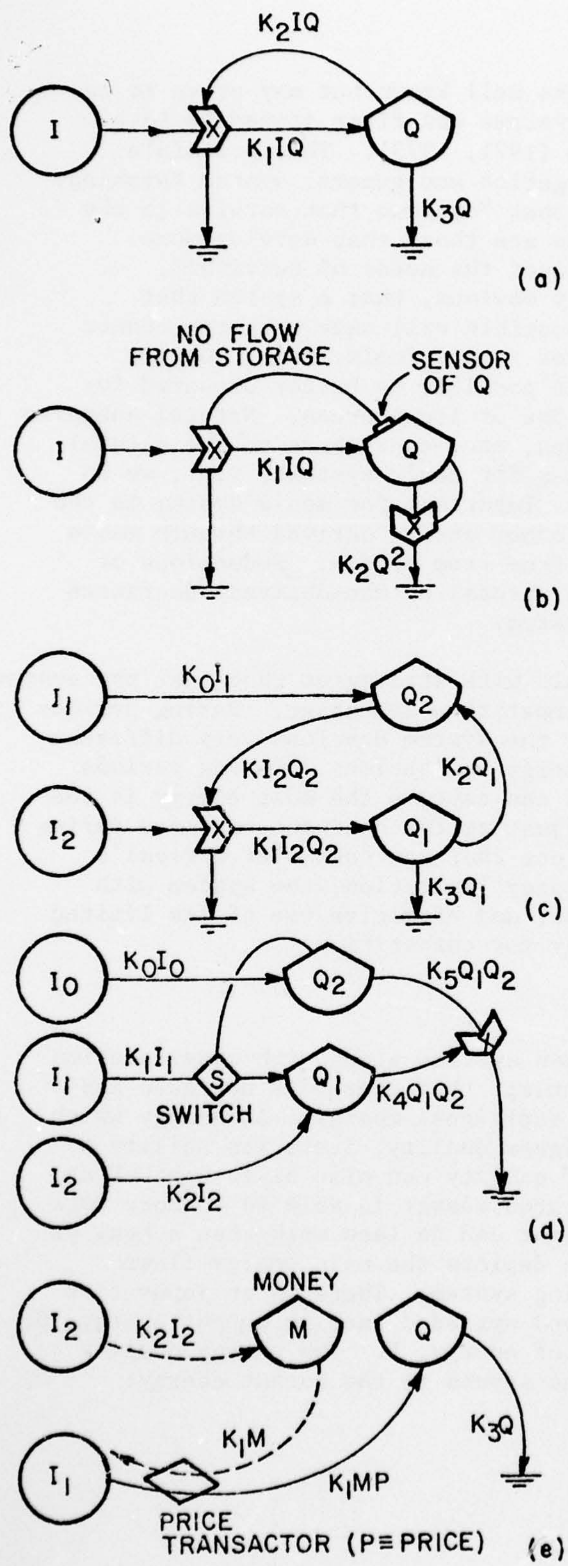
a. Storage with linear inflows and outflows.

b. Sensor of storage, Q; there is no flow associated with a sensor.

c. Two interconnected storages.

d. Two storages with switch controlling $K_1 I_1$ inflow into storage Q_1.

e. Diagram illustrating money transactor. The flow of goods or energy is equal to the money flow multiplied by the price.



(a)

$$\frac{dQ}{dt} = K_1IQ - K_2IQ - K_3Q$$
$$I = f(t)$$

(b)

$$\frac{dQ}{dt} = K_1IQ - K_2Q^2$$

(c)

$$\frac{dQ_1}{dt} = K_1I_2Q_2 - K_2Q_1 - K_3Q_1$$

$$\frac{dQ_2}{dt} = K_0I_1 + K_2Q_1 - KI_2Q_2$$

(d)

$$\frac{dQ_1}{dt} = K_2I_2 + K_1I_1 - K_4Q_1Q_2 \qquad Q_2 > Q_T$$

$$\frac{dQ_1}{dt} = K_2I_2 + 0 - K_4Q_1Q_2 \qquad Q_2 < Q_T$$

$$\frac{dQ_2}{dt} = K_0I_0 - K_5Q_1Q_2$$

Q_T = THRESHOLD VALUE FOR Q_2.

(e)

$$\frac{dM}{dt} = K_2I_2 - K_1M$$

$$\frac{dQ}{dt} = K_1MP - K_3Q$$

A third energy principle which is less well known but may prove to be of value for understanding general systems was first stated by Lotka (1922) and further developed by Odum (1971, 1973). This principle combines natural selection with energetics and general system thinking. This maximum power principle states that "systems that survive in the competition among alternative choices are those that develop more energy inflows and use them best to meet the needs of survival". The first part of this is intuitively obvious, that a system that develops as many energy sources as possible will have a better chance of survival. A human system that uses fossil fuels, solar energy, nuclear energy, and as many others as possible is better prepared for fluctuations and limitations of any one of its sources. Natural energies such as those of the sun, winds, tides, etc. contribute to the natural ecosystems and are free energy sources for man's systems, i.e., we do not pay for the air we breathe, etc. Important for man's system is the total energy, both fossil fuels and other energy derived through man's efforts and those that are provided free from nature. Reductions or decreases in any energy source (both natural or man-derived) decreases the total energy available to the system.

The second part of the principle deals with strategies that that the system can do internally to increase its competitive advantage. During periods when external energies are abundant, the system develops very different strategies than during periods of energy limitations. During periods of energy expansion, the system that can capture the most energy is the one that is most likely to survive (just as the dominant business during an expanding economic period is the one that can take over a rival's business). But during periods of energy limitation, the system with the least waste, with efficient, wise, and effective use of its limited resources will have a better strategy for competition.

Energy Quality

Investigations of ecosystems and human systems along with consideration of Lotka's principle leads to the concept that energy is upgraded and stored to accelerate the capture of additional energy. An energy which is upgraded can be said to have a higher quality, i.e., its ability to do work is greater. This concept of quality can also be thought of as energy concentration, i.e., concentrated energy is able to do more work than dilute energy. A kcal of sunlight can do less work than a kcal of fossil fuel. Consider Fig. 3a which depicts the main energy flows associated with an energy transforming system. There is an input flow of energy, I, which is transformed and upgraded into an output energy, O, with the aid of an auxiliary source of energy, F. The energy quality factor is defined as the ratio of the inputs to the output energy:

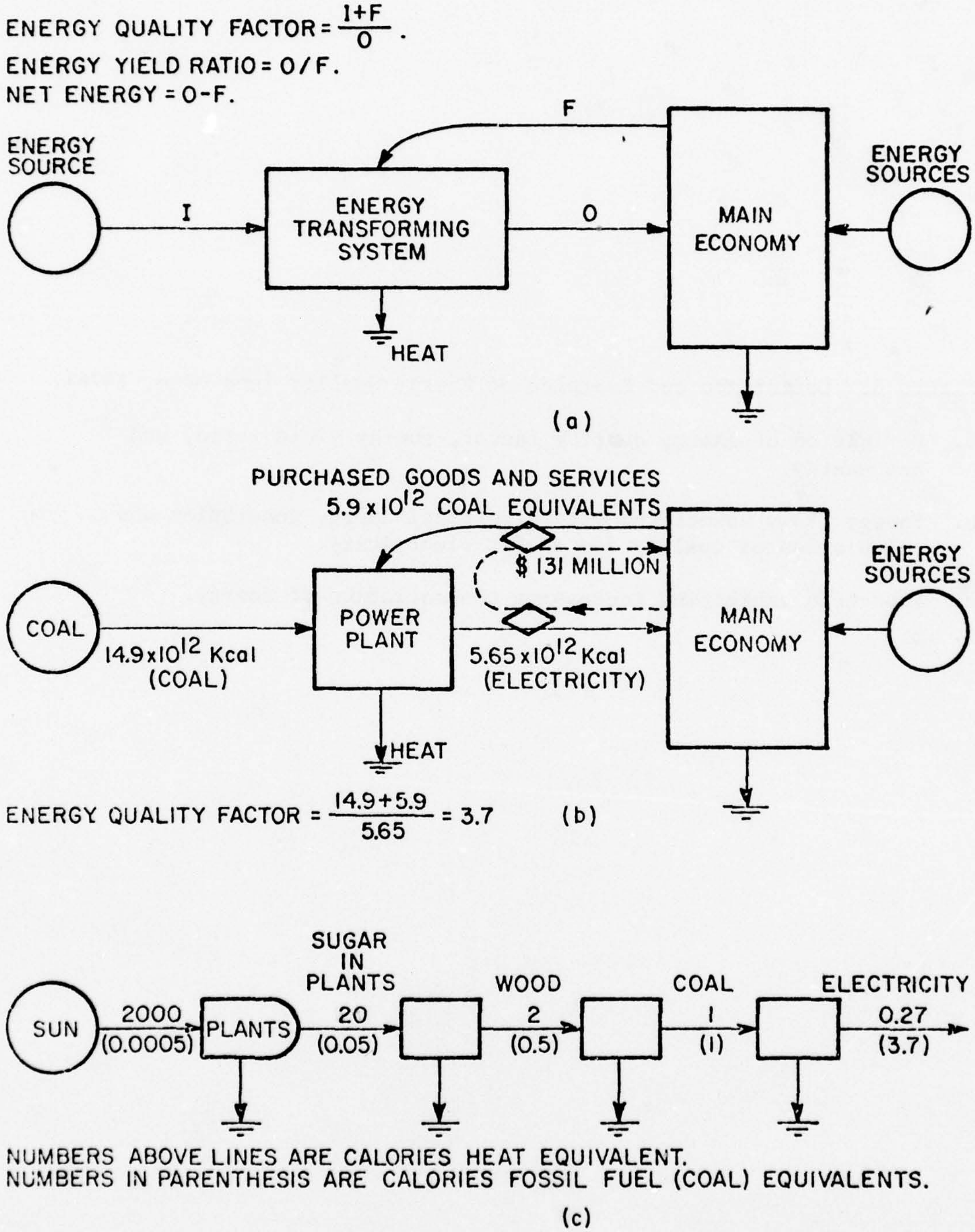
$$\text{Energy Quality Factor} = \frac{I + F}{O}$$

Figure 3. Definition and Examples of Energy Quality (see Odum, 1976).

a. Definition of energy quality factor, energy yield ratio, and net energy.

b. Energy flows associated with electrical energy generation and calculation of quality factor for electricity.

c. Foodchain exhibiting increasing concentration of energy.



ENERGY QUALITY FACTOR = $\frac{I+F}{O}$.
ENERGY YIELD RATIO = O/F.
NET ENERGY = O-F.
ENERGY SOURCE
I
F
ENERGY TRANSFORMING SYSTEM
O
MAIN ECONOMY
ENERGY SOURCES
HEAT
(a)
PURCHASED GOODS AND SERVICES
5.9×10^{12} COAL EQUIVALENTS
\$ 131 MILLION
COAL
14.9×10^{12} Kcal (COAL)
POWER PLANT
5.65×10^{12} Kcal (ELECTRICITY)
MAIN ECONOMY
ENERGY SOURCES
HEAT
ENERGY QUALITY FACTOR = $\frac{14.9+5.9}{5.65} = 3.7$
(b)
SUN
2000 (0.0005)
PLANTS
SUGAR IN PLANTS
20 (0.05)
WOOD
2 (0.5)
COAL
1 (1)
ELECTRICITY
0.27 (3.7)
NUMBERS ABOVE LINES ARE CALORIES HEAT EQUIVALENT.
NUMBERS IN PARENTHESIS ARE CALORIES FOSSIL FUEL (COAL) EQUIVALENTS.
(c)

For example, Fig. 3b shows the upgrading of coal to electricity in a power plant. The auxiliary flow of energy, F, is the energy associated with the goods and services necessary for a power plant. The energy quality factor is the number of calories of input energy which is equivalent to 1 calorie of output energy. Theoretically, 3.7 heat calories of coal can do the work of 1 heat calorie of electricity or 0.27 (1/3.7) heat calories of electricity can do the same work as 1 heat calorie of coal. If there is no auxiliary source, F, then the energy quality factor is simply the input divided by the output, I/O. The green plant is an example for which sunlight is converted to sugar, for which the ratio of input to output energy is approximately 100.

In natural ecosystems, a food chain develops which concentrates energy from sunlight up to the top carnivores. The chain and upgrading of energy which exists in human systems is depicted in Fig. 3c with approximate magnitudes of energy flow (Odum, 1976). Fig. 3c illustrates that 2,000 heat calories of sunlight, 20 heat calories of sugar in plants, 2 heat calories of wood and 0.27 heat calories of electricity are equivalent to 1 heat calorie of coal. In theory, if energy concentration factors could be developed for all types of energy, then energies of different concentrations could be compared on an equal basis as to their ability to do work. Tentative energy concentration factors for several types of energy are listed in Table 2. Dividing a given type of energy flow by this factor will give the energy value in units of fossil fuel coal equivalents (FFCE). For example, 1 kcal (BTU) of sunlight is equivalent to 1/2,000 kcal (BTU) of fossil fuel (coal). Unless otherwise specified a unit of energy (either kcal or BTU) will be in units of coal energy (FFCE = fossil fuel coal equivalent) and will be used in this way throughout the text. If the heat value of a given energy flow is referred to, it will usually be called a heat calorie.

Energy Basis for the System of Man

Based on the observation that all systems are driven by external energy sources, Fig. 4 is a simple diagram showing the relation of money flow to energy flow with the system driven by external sources of solar energy and fossil fuels. Primitive and agricultural societies were driven primarily by solar energy flows. Since the 19th century the flow of fossil fuels has increased dramatically. In this conception of the system of man, it is energy that generates value with money flowing in a countercurrent direction. Much of the work of the natural systems generated by solar energy is not paid for with dollars by man. In essence, this is a free subsidy. If the total solar energy falling on the U.S. per year is divided by 2,000 to find its equivalent fossil fuel work and this is added to the fossil fuel consumption in a year, the result is the total work provided to the system of man. Dividing this by the GNP gives an average energy/dollar ratio for the economy in

Table 2

Energy Quality Factors Showing Estimates of Energy Required for Transforming Energy of Different Qualities to that of Coal under Competing Cicumstances

Type of Energy	Number of Units of Energy Equivaent to one Energy Unit of Coal[a]
Solar Energy in Photons	2,000
Photosynthetic Products	20
Wood	2
Geothermal Steam	1.6
Coal already mined	1 (by definiticn)[b]
Tidal Energy, 20 ft tide	0.6
Elevated Water	0.62
Electricity	0.27

[a]The numbers in this column are the number of calories (BTU's) of the given type of energy which are equivalent to 1 calorie (BTU) of coal. Energy Quality Facotrs are preliminary and subject to reajustments. See Odum et al. (1976), Odum (1974), Kemp (1974), Young et al.(1974), Costanza (1975), and Boynton (1975).

[b]A unit of coal energy is referred to in the text as a fossil fuel work equivalent or coal equivalent (FFWE, FFCE, FFE or CE).

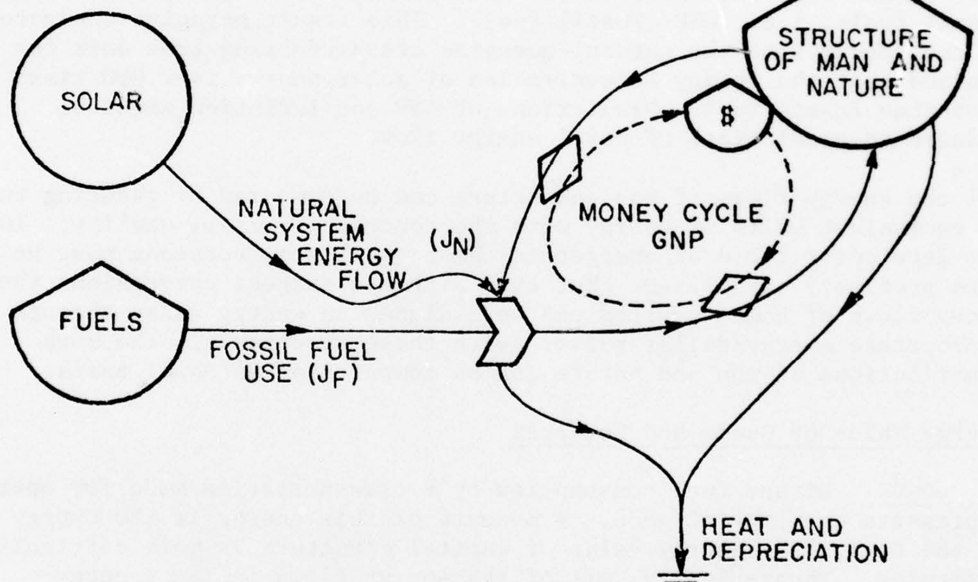


Figure 4. Simplified Diagram of the U.S. Economy Showing Main Flows of Natural Energies and Fossil Fuel Energies into the U.S. Economy and Associated Cycle of Money Flow (see Table 3 and Odum, 1973).

a given year. This ratio is the amount of energy necessary to generate one dollar of economic value. Kylstra (1974) has calculated these ratios from 1947-72 (see Table 3). The ratio of (Fossil Fuels + Natural)/GNP in current dollars was approximately 18,700 kcal/$ for 1974. Different sectors of the economy will have different energy/dollar ratios. For example, steel or cement industries will have a high energy/dollar ratio whereas a service sector will have a much lower ratio.

It is interesting to note that the total energy/dollar ratio has been decreasing, i.e., one dollar does less work. This can be thought of as the cause of inflation, i.e., the ratio of dollars to energy is increasing. In fact. R. Walker (1976) and T. Ballentine (1976) have shown that the rate of increase of the ratio of GNP/(Fossil Fuel + Natural) is exactly the same as the rate of inflation in the periods 1965-70 and 1970-72. This is not true for the ratio which just considers fossil fuels, i.e., GNP/(Fossil Fuel). This result may give credence to the theory that the natural energies are performing free work for man and that the energy concentration of solar energy is 2,000 times less than fossil fuel. Predictions of GNP and inflation might be reduced to predictions of total energy flow.

All the energy flows of man and nature can be compared by reducing them to equivalent units of energy with the concept of energy quality. In the developing field of energetics these quality conversions must be more precisely quantified. But even with the current conversions the money flows of human systems can be assigned an energy value through an appropriate energy/dollar ratio. With these theories all the work contributions of man and nature can be compared on an equal basis.

Energy Value of Goods and Services

1. Goods. Direct fuel consumption by a transportation mode for operation represents one type of good. A measure of this energy is the energy value of the fuel. The energy value of capital structure is more difficult to determine. Theoretically, all of the energy flows in the economy associated with the industry producing the capital structure should be determined. This includes all the flows of energy from the raw materials to the creation of the product. Each material should be traced back to its source. Similarly, every energy flow associated with material flows should be traced back to the fuel source. There are two ways that one might determine the energy required to create capital structure. The first of these, process analysis, determines the quantity of materials that went into a product (e.g., a barge). These materials are traced back to their raw material origins. Both direct and indirect energies at every step along a material path should be included. For example, Fig. I-1 in Appendix I is an attempt to include all energy pathways required for the construction of a barge. A sum of the energies for all

Table 3

Ratio of Energy Flows in U.S. Society to GNP
(Adopted from Kylstra, 1974)

Year	Fossil Fuels $10^{15}KC_{FFCE}/yr$ (J_F)	Fossil Fuels Plus Natural $10^{15}KC_{FFCE}/yr$* (J_F+J_N)	GNP** $10^9\$$	Fossil Fuel Plus Natural per GNP $10^3KC_{FFCE}/\$$***	Fossil Fuel Plus Natural per GNP 10^3 BTU(FFCE)/$
1947	8.28	15.02	231.3	64.9	257.7
1948	8.57	15.31	257.6	59.4	235.8
1949	7.96	14.70	256.5	57.3	227.5
1950	8.60	15.34	284.8	53.9	214.0
1951	9.30	16.04	328.4	48.8	193.7
1952	9.22	15.96	345.5	46.2	183.4
1953	9.50	16.24	364.6	44.5	176.7
1954	9.16	15.9	364.8	43.6	173.1
1955	10.07	16.81	398.0	42.2	167.5
1956	10.58	17.32	419.2	41.3	164.0
1957	10.56	17.30	441.1	39.2	155.6
1958	10.46	17.20	[illegible]7.3	38.4	152.4
1959	10.94	17.68	483.7	36.6	145.3
1960	11.33	18.07	503.7	35.9	142.5
1961	11.52	18.26	520.1	35.1	139.3
1962	12.06	18.80	560.3	33.6	133.4
1963	12.51	19.25	590.5	32.6	129.4
1964	12.98	19.72	632.4	31.2	123.9
1965	13.60	20.34	684.9	29.7	117.9
1966	14.40	21.14	749.9	28.2	112.0
1967	14.68	21.42	793.9	27.0	107.2
1968	15.56	22.30	864.2	25.8	102.4
1969	16.37	23.11	930.3	24.8	98.5
1970	16.94	23.68	976.4	24.3	96.5
1971	17.33	24.07	1050.4	22.9	90.9
1972	18.17	24.91	1151.8	21.6	85.8
1973	19.08	25.82	1289.1	20.0	79.4
1974	19.4	26.14	1397.4	18.7	74.2

*Solar energy contribution to the U.S. is estimated at 6.74 x $10^{15}KC_{FFCE}/$ yr. This was obtained by taking the sunlight falling on the U.S. land area and dividing by 2,000 to obtain fossil fuel work equivalents.

**GNP is expressed in current dollars.

***FFCE is a unit of coal energy (kcal or BTU).

pathways gives the total energy for constructing a barge. The inclusion of the energy of labor is discussed on p. 22. The method described above, if carried through in detail, would result in accurate energy values and avoid estimation from economic information with the use of energy to dollar conversion factors. Thus, each component of a system could have an energy value assigned to it.

A second method consists of determining detailed energy to dollar ratios for sectors of the economy allowing calculation of energy flows from economic flows. Herendeen and Bullard (1974) have used input-output sectors in the economy. If a dollar value of goods from a given sector in the economy is known, then all fossil fuel energies required for the creation of that product can be approximated by multiplying the dollar value by the appropriate energy to dollar ratio. This energy consists of energy directly used in the given sector plus indirect energies used in other sectors which are connected to the economic sector under consideration. This analysis is a valiant attempt to determine the direct and indirect fossil fuel energies necessary to produce a dollar value of goods for different sectors. However, this analysis does not include the free natural energies contributing to the economy of man. We include this in our analysis as follows: an approximate natural energy/dollar ratio in a given year that should be added to the fossil fuel/dollar ratio is 6.74×10^{15} kcal divided by the GNP for that year (see Table 3). The energy of labor is not included in this I-O analysis and the energy/dollar ratios are calculated for 1963 and 1967 although approximations were made for other years. Knowing the energy/dollar ratios for 1967, the ratios in future years can be approximated by the following formula:

$$E_j(y) = E_j(1967)\ \frac{E(y)/GNP(y)}{E(1967)/GNP(1967)} \times \frac{\text{Price Index}_j\ (1967)}{\text{Price Index}_j\ (y)}$$

where:

$E_j(y)$ = energy/dollar ratio for a given I-O sector j in year y
This energy includes only fossil fuel.

$E(y)$ = fossil fuel energy consumption in year y for entire economy

$GNP(y)$ = gross national product in constant dollars for year y

$\text{Price Index}_j(y)$ = price index for given sector in year y

Variables with 1967 in parenthesis refer to values in year 1967.

The above equation accounts for changes in the average energy to dollar ratio for the entire economy with the ratio:

$$\frac{E(y)/GNP(y)}{E(1967)/GNP(1967)}$$

The effect of greater dollar flow due to inflation in a particular sector is accounted for by the ratio of the price indexes for that sector as given by

$$\frac{\text{Price Index}_j(1967)}{\text{Price Index}_j(y)}$$

As outlined above, using energy/dollar ratios for individual economic sectors is a refinement compared to just using the average ratio for the economy as listed in Table 3. Values from sector to sector can differ by an order of magnitude. Wherever possible, individual sector values have been used for calculations in this report. It should be remembered that E_j represents a fossil fuel energy to dollar ratio. As alluded to above, the natural energy to dollar ratio for a given year should be added to this. In reality a combination of tracing back of the material flows and the use of energy to dollar ratios will probably be necessary in trying to establish energy values for transport capital structures (see Appendices).

The use of economic flows to calculate energy flows means that the economic system is used as an indicator of energy value. However, since energy/dollar ratios vary significantly between I-0 sectors, a dollar's energy value differs depending on its position in the economy. A pure energy approach would attempt to elaborate pure energy flows throughout the economy. Unfortunately, this data is not now readily available so that dollar flows are still necessary for making energetic calculations.

If the total existing stock of capital structure in energy units of a system is desired then the energy invested in any given year must be calculated and then depreciated to the present. This can be expressed as follows:

$$\text{Total Capital Structure} = \sum_{i-o}^{N} D_i \; R_i \; (1-d)^N$$

where D_i = capital dollar flow invested in the i^{th} year

R_i = energy/dollar ratio in the i^{th} year in current dollars

d = depreciation rate

N = number of the years to consider before present time

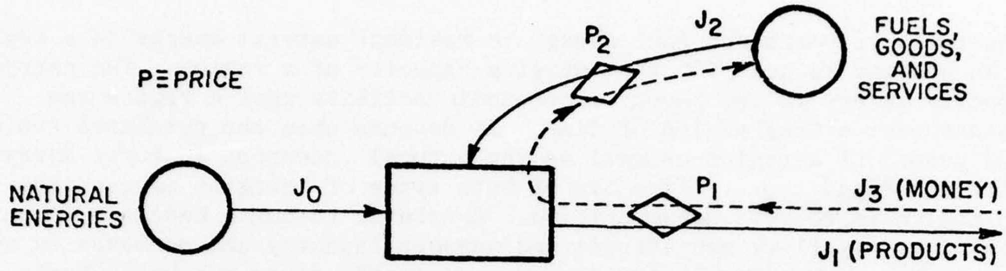
i=o = the present year

2. Labor. Since labor is a major requirement for many systems of man, the energy value of labor needs to be considered. The energy requirement of labor can be thought of as the energy the workers require to purchase goods and services to maintain their standard of living. Presumably, this standard of living is necessary for the workers to function in a complex society. Higher wage demands above and beyond the effects of inflation will result in greater energy consumption in the larger economy to provide for this greater demand. The energy requirement of labor in this sense is broader than just the metabolic or chemical energy of the laborer.

The question arises as to how to include the energy cost of labor into an energy analysis. It seems that the answer to this question depends on the problem under study. In general, only the direct labor required for a given process should be included as an energy cost. For example, if the energy cost of the construction of a barge is to be determined, the labor directly involved in the barge construction should be included but not the labor involved in other industries such as steel, electrical, etc. connected with the barge. This is because the energy cost of labor in the other sectors has been included in the total cost of those goods. The energy cost of labor is included in the final step so that alternative transport systems may be compared with the inclusion of labor. Labor is a significant cost in many operations and can vary in the different systems. Generally the energy cost of labor is included in the wage of the laborer converted to an energy basis. In this way an energy comparison between two transport systems can be made with direct labor included as an energy cost.

Investment Ratio and Economic Competitiveness

An approach which attempts to combine the energy flows of the systems of man and nature with the concept of economic competitiveness has been proposed by H.T. Odum et al. (1975, 1976). Although this approach is not used in this report, an explanation is provided in order to show the various developments of energy theory. Consider Fig. 5 which illustrates the concept in its simplest and most basic form. The rectangle in the diagram represents any system (e.g., a particular region of the U.S.) with a flow of natural energies (J_0) and a flow of fossil fuel energies in the form of fuels, goods, and services (J_2). The flow, J_1, represents exports produced from the inflow energies, J_0+J_2, which generate an income, J_3, to be used for additional purchases of fossil fuel investment. All energy flows are expressed in units of equivalent energy quality. If the ratio of purchased energies, J_2, to free natural energies, J_0, is low compared to a competing system, then the system with the lower ratio should be able to sell at a lower price and compete better because of its greater free energy subsidy, J_0. The ratio of purchased energies to free natural energies with energies expressed in equivalent units of energy, J_2/J_0, is called the investment ratio.



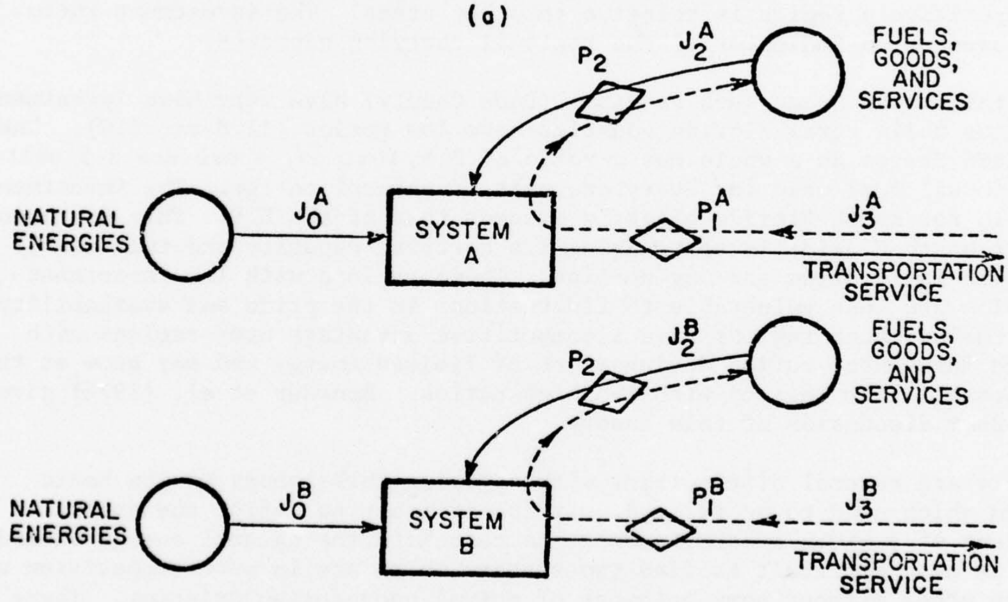
$$J_1 = K(J_0 + J_2) \qquad P_1 = \frac{J_3}{K(J_0+J_2)} = K_1\frac{J_2P_2}{J_0+J_2}$$

K, K_1 ARE CONSTANTS

$$P_1 = K_1P_2\frac{J_2}{J_0+J_2} = \frac{J_2/J_0}{1+(J_2/J_0)}$$

J_2/J_0 = INVESTMENT RATIO

(a)



$$P_1^A = K_2P_2\frac{J_2^A}{J_0^A+J_2^A}\ ;\ P_1^B = K_3P_2\frac{J_2^B}{J_0^B+J_2^B}$$

$I = J_2/J_0$

$$P_1^A/P_1^B = K_2/K_3\,\frac{(J_0^B/J_2^B)+1}{(J_0^A/J_2^A)+1} = K\,\frac{(1/I^B)+1}{(1/I^A)+1}$$

K = CONSTANT

$K = K_2/K_3$

(b)

Figure 5. Diagram Illustrating the Relationship of Natural Energies, Fossil Fuel Energies, and Prices.

a. Definition of investment ratio for a region.

b. Relationship of natural energy subsidies and prices for a transportation system.

This ratio of purchased fuel energy to resident natural energy in a region is an attempt to quantify the carrying capacity of a region. The carrying capacity refers to the amount of economic activity that a region can sustain over a long period of time. It depends upon the purchased fuels (and goods) of a region as well as the natural resources (natural energies) which are found there. Wise use of both types of energies is required if the region is to remain competitive. A natural resource base (or a healthy natural energy flow) can attract and support industry and commerce in an area. When such natural resources are available fewer purchased fuels are needed in the area. For example, a region with abundant fresh water is better able to support commerce than a region which must purchase water or build large scale water projects. Those areas that must purchase or build water projects must pay higher costs and so are at a competitive disadvantage. Since the investment ratio requires calculation of both natural and purchased energies it can be used as an indicator of how competitive a region is relative to other areas. The investment ratio is used as an indicator of the regional carrying capacity.

Certain urban areas such as Miami (Dade County) have very high investment ratios while rural Florida counties have low ratios (11.8 vs. 1.0). The United States as a whole has a ratio of 2.5, that is, there are 2.5 units of fossil fuel used for every one unit of natural energy. The investment ratio for south Florida slightly exceeds that of the U.S. This may mean that south Florida is approaching its carrying capacity and that its growth is leveling and may decline. Those regions with low investment ratios are less vulnerable to fluctuations in the price and availability of fuels. Such regions have a competitive advantage over regions with high investment ratios during times of limited energy and may grow at the expense of the regions with the high ratios. Browder et al. (1976) gives further discussion of this theory.

There are several difficulties with applying this theory in its basic form which need to be refined. It is difficult to define the spatial extent of a given system in order to calculate the natural energy subsidies. It is also difficult to find two systems which are in pure competition with each other without some pathways of mutual cooperation existing. There is also the question of the time delay between a system reaching a threshold value for the investment ratio and its becoming non-competitive. For example, New York City has probably had a high investment ratio for many years while at the same time being economically competitive. It is only in recent years that it has begun to suffer economic difficulties such as high debt and loss of industries to other cities. Odum et al. (1975) suggests that during times of increasing and inexpensive energy, those systems which have the greater investment ratio can compete better because they have more storage and structure built with which to capture additional energies; whereas during times of declining energies, those systems with greater free energy subsidies can compete better

Even though the investment ratio may provide only a first approximation, it is an attempt to determine the regional carrying capacity. Fig. 5b applies this concept to two competing transportation systems. Each one has a flow of natural energies, J_0, a flow of fossil fuel energies, J_2, a flow of money, J_3, a price for the transportation service, P_1, and a price for the external energies, P_2. Following from Fig. 5a, the prices $P_1{}^A$ and $P_1{}^B$ can be solved for in terms of the energy flows and external price, P^2. If it is assumed that this external price for goods and services is equal for both systems, then the ratio of $P_1{}^A/P_1{}^B$ can be solved for in terms of the energy flows. It can be seen from the equations in Fig. 5b that if $I^A < I^B$ (I = investment ratio = J_2/J_0), then $P_1{}^A < P_1{}^B$. Thus, for two competing transport systems providing equivalent service, the system which must charge the higher price will eventually be forced out of business.

Natural Energies and Transport Systems

Following from the above discussion, the inclusion of natural energy considerations is as follows:

1. A natural energy subsidy to a transportation system should lower the price of that particular service since this energy does not have to be paid for with money (e.g., going downstream on a river by barge). (See discussion of investment ratio on p. 22 and Fig. 5). It is sometimes difficult to decide what the natural energy subsidies are for a transportation system. For example, what is the natural energy subsidy for a waterway transportation system? Is it kinetic energy of the water which is a subsidy when traveling downstream or is it the potential energy of the water in the drainage basin which is responsible for the existence and creation of the waterway system? Several calculations of natural energy contributions are discussed in section III-A.

2. Natural energy destrcution by a transportation system or project will lower the work capacity of the natural systems. As explained above, the natural systems of the world provide economically free work for the systems of man. Determining the work lost due to a particular project entails calculations of the energy loss (e.g., photosynthetic production) and conversion of this energy to equivalent units of fossil fuel work. The natural energy losses for the railroads can be partially accounted for by calculating the destrcution of photosynthetic productivity. The effects of barge transportation must be related to the distrubances of aquatic productivity and river flow characteristics.

Energy Budget, Net Energy and Energy Yield Ratio

The major flows of energy in a transport system consist of fuels, capital investment, labor, and natural energies. Different types of capital investment would have differing energy/dollar ratios, e.g., barges as compared to buildings. In general, the total energy costs per year to a system could be computed from the following formula where all energies are expressed in kcal or BTU of coal (FFCE):

$$J_T = J_F + \sum_i M_{ci}R_{ci} + M_L R_L + J_N$$

where J_T = total energy input

J_F = energy value of fuels

M_{ci} = money invested per year for i^{th} component of capital investment

R_{ci} = energy/dollar ratio for i^{th} component of capital investment

M_L = wages of labor

R_L = energy/dollar ratio for labor

J_N = natural energy losses from destruction of natural system. All energies should be expressed in equivalent units of energy, e.g., fossil fuel coal equivalents (FFCE).

All flows should be over an equivalent time, e.g., one year. Knowing the total tons (T) shipped in that year and total distance traversed (D) allows a calculation of the total energy/ton-mile:

or $j_t = J_T/TxD)$

This can serve as a comparison between different systems. This ratio can also be calculated in different years for the same system in order to compare changes in total energy use.

The above index, j_t, of total energy/ton-mile might represent an overall average energy cost for a transportation system irrespective of the type of good shipped. In particular, if a good being shipped is a fuel with an energy value per ton, j_0, then the net energy of transport (energy delivered minus energy required to deliver) is:

$$J_{NET} = j_0{}^T - j_t(TxD) = T[j_0 - j_tD]$$

where J_{NET} = net energy of transport = energy delivered minus energy required to deliver

j_0 = energy value per ton of the fuel shipped

j_t = total energy per ton-mile for the transport system

T = number of tons of fuel shipped

D = distance fuel is shipped

The concept of net energy outlined above is closely related to Lotka's maximum energy principle since minimizing the energy invested per unit of energy delivered for transportation allows more energy to be invested in other sectors of the economy for the creation of economic value. In essence, maximizing the net energy of transportation helps to maximize the net energy to society as a whole. This seems to correspond to maximizing net benefits in economic benefit/cost analysis but with the inclusion of natural energies.

When considering the transport of fuels it is of interest to calculate the energy transported per unit of energy cost. This ratio is referred to as the energy yield ratio and is defined as

$$\text{Energy Yield Ratio} = \frac{\text{Energy Delivered}}{\text{Energy Cost to Deliver}}$$

$$= \frac{1}{D} \times \frac{j_0}{j_t}$$

A consideration of the energy value of goods can also lead to interesting import-export considerations. For example, trading American wheat for Russian oil could be looked at in terms of the energy required to produce and transport the wheat as compared to the energy value of the petroleum exchanged. If the value of the petroleum is greater than the energy cost of the wheat, then the result is a net energy growth to the economy. Odum et al. (1976) has calculated that the trading of wheat for petroleum has a yield approximately of five for the U.S. That is, the energy cost related to the wheat is five times less than the energy value of the imported petroleum.

Spatial Energy Theory for Determining the Competitive Position of a Fuel Source

Other sections have detailed methods and calculations for determining the total energy input required, both direct and indirect, for a given transportation system. In particular, if a transport system is carrying a fuel (e.g., oil or coal), then the energy required to transport a unit of energy can be calculated and a quantity called the "net energy of transport" can be defined as the energy transported minus the energy required for transport. A transportation planner or analyst could then use a net energy criteria to choose a transport system which delivers the greatest energy per unit invested. However, transportation planning and analysis is not restricted solely to the transport system, but also should include the effects and interactions that occur at the supply center, demand center, and along the transportation right of way. This is discussed in detail in section IV on the Northern Great Plains. The concept of net energy can be extended beyond the transportation system as illustrated in Fig. 6 in order to define parameters which might be useful for national planning of energy development and transportation systems.

Consider Fig. 6 which illustrates the combination of two sectors involved in the delivery of coal resources, namely, a mining sector and a transportation system. In order to get the coal resource out of the ground, energy investment in the form of capital investment and maintenance (J_2^{1}), labor (J_2^{11}), andfuels (J_3) is required. Associated with the mining is a loss of natural energies (J_1) which might consist of losses associated with photosynthetic production, wildlife, geological structure, etc., while J_0 represents losses due to effects on other economically productive systems (e.g., agriculture). For the mining sector at steady-state, the input of capital investment and maintenance plus labor ($J_2^{1} + J_2^{11}$) would equal the depreciation, J_2. The energy cost of mining an amount of coal J_4 is $Q_1 = (J_0+J_1+J_2+J_3)$, so that *the net* energy of mining is J_4-Q_1. The required energy investment per unit of coal energy mined is a function of the depth and quality (BTU's/lb) of the coal. Deeper coal requires more fuel and equipment to mine, whereas low quality coal requires more tons to be mined for a given energy output. The ratio of energy output to energy investment, J_4/Q_1, is sketched in Fig. 6 to show its probable relationship as a function of coal depth and quality.

Associated with any mining operation will be a transport system for distribution of the resource. As discussed in previous sections and as outlined in Fig. 6, there is an energy cost associated with the transport system equal to $Q_2 = J_5+J_6+J_7$. It is assumed that these costs also include those associated with loading and unloading the coal. If it is assumed that there are no coal losses, then the ratio of coal energy transported, $J_8 = J_4$, to the energy cost of transport, Q_2, is J_4/Q_2. This ratio will decrease with increasing distance of transport, D, as is illustrated in Fig. 6. This functional relationship will differ for different transport systems. If the total cost of both mining and transport is considered, then the overall cost is $(Q_1 + Q_2)$, the net energy is $J_4 - (Q_1 + Q_2)$, and the yield ratio of energy delivered to energy cost is $Y = J_4/(Q_1 + Q_2)$.

As outlined in the previous paragraphs, the yield ratio, Y, will be a function of the type of coal mine, the transportation system, and the distance transported. This ratio may be useful for making decisions about national energy policy since it is a measure of the energy cost of delivering a given type of energy. Figure 7 depicts three sources of coal at points A, B, and C (e.g., these might represent three coal mines

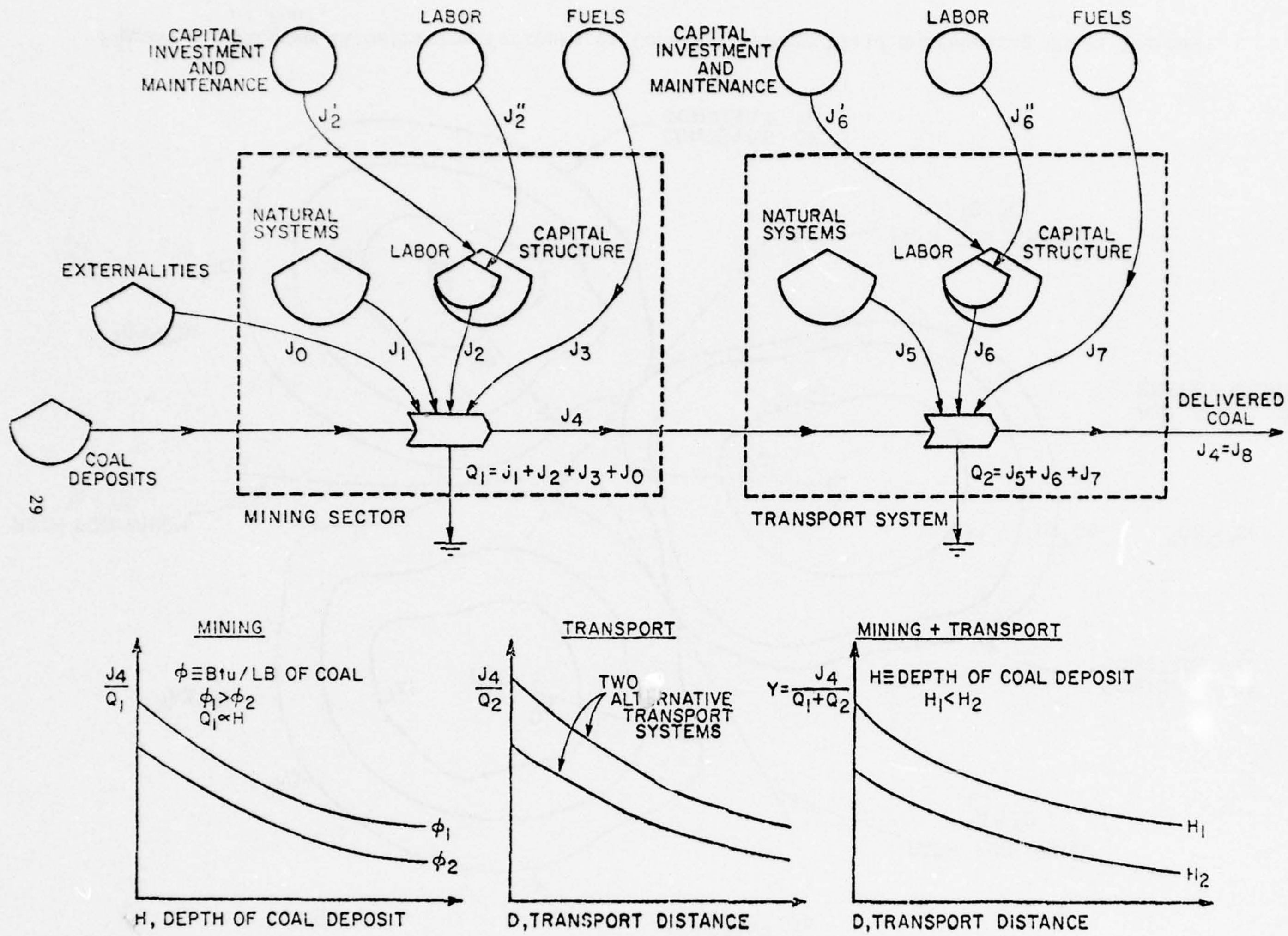


Figure 6. Diagram Showing the Major Energy Costs Associated with the Mining and Transport of a Fuel with Probable Relationships Between Energy Yield Ratios, Energy Content of Fuel, and Distance Transported.

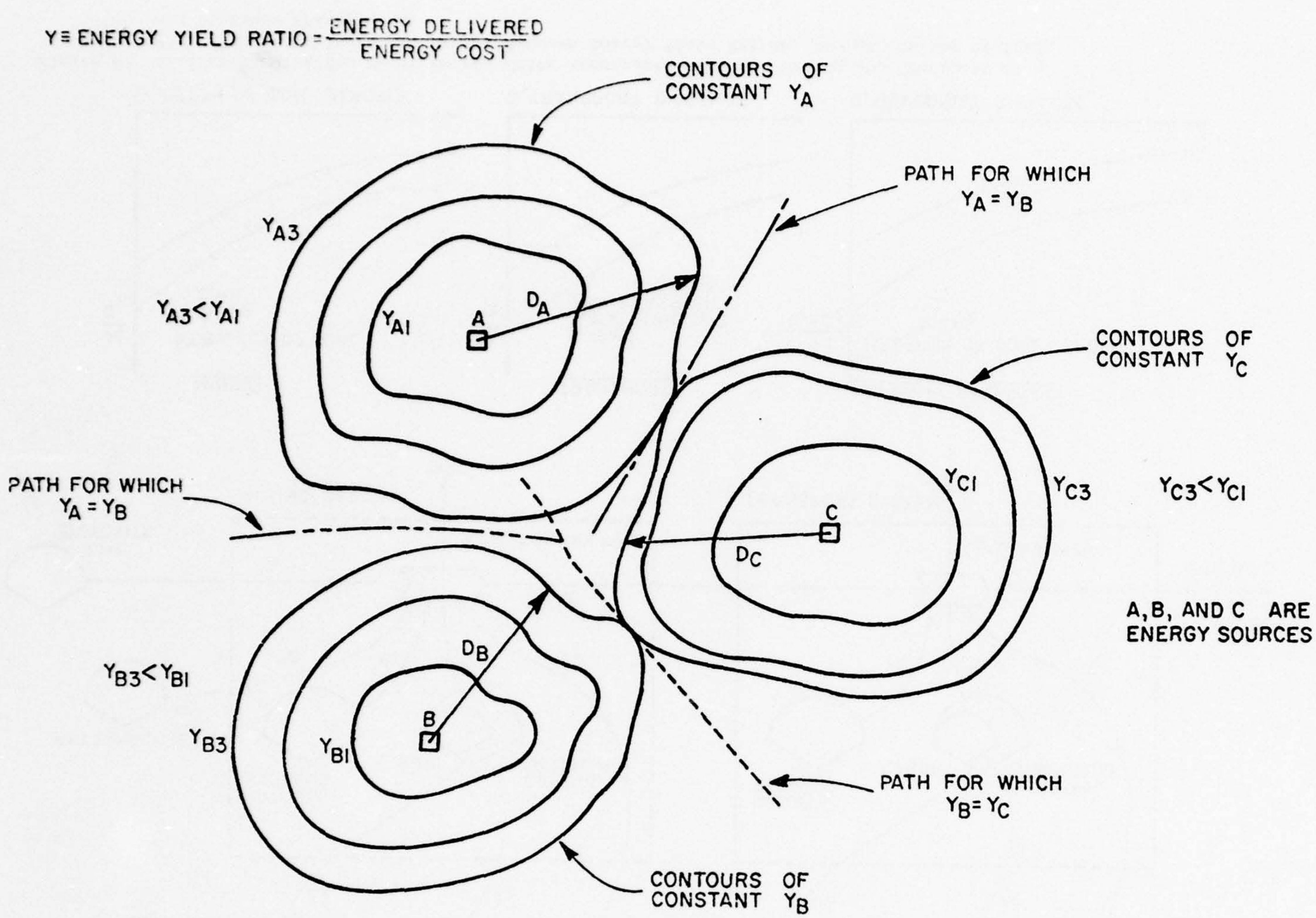


Figure 7. Diagram Illustrating Contours of Constant Energy Yield Surrounding Three Sources of Fuel.

or coal mining regions in the U.S.). Following from the discussion in previous paragraphs, the energy cost of mining and transport could be calculated and contours of constant yield ratio, Y, calculated for each energy source (see Fig. 6 and previous paragraph for the definition of yield ratio). The transport of a unit of energy from a source might involve more than one kind of transport mode: the energy cost of each mode per unit of energy shipped would need to be determined. As depicted in Fig. 7 there will exist trajectories along which the yield ratio for two sources will be equal, e.g. $Y_A = Y_C$. Coal delivered from the source, C, to any point between C and this trajectory will have a higher yield ratio than coal originating from source B. It could be said that source C is energetically more competitive in this region than source B because it costs less energy per unit of energy output. It should be remembered that the energy cost in this analysis includes natural energy losses; thus an economic analysis which predicted competition based on price would arrive at different results unless an accurate economic value were placed on natural system losses. Maps such as Fig. 7 could be constructed for domestic sources of coal, oil, and natural gas for different types of transport systems. Combining these graphs could define regions of maximum energy yield for each energy source.

This type of analysis could be extended to non-energy sources, e.g., steel. In this case the fossil fuel and natural energy losses associated with producing a unit of steel would have to be determined along with the energy transport costs. Contours of constant energy cost could be constructed around each source which would indicate the total energy cost of delivering a unit of steel. Regions of energetic competitiveness could be determined.

Energy Theory and Transportation Models

This section presents a brief overview of how energetic considerations might be used to modify transportation models currently used.

1. Network analysis is used extensively for studying the spatial properties of transportation systems with measures of connectivity, redundancy, etc. However, trying to predict how transportation linkages may increase or contract spatially in response to available fuels would constitute a viable research problem. This kind of approach might be especially important to developing countries and the U.S. as energy sources change.

2. The gravity model is one of the most common formuations for predicting traffic flows between traffic generators. In analogy to Newton's law of gravitation its form is:

$$l_{ij} = F \frac{(P_i P_j)}{(d_{ij})}$$

where l_{ij} = number of interactions between regions i and j

F = empirical constant

P = some measure of the size or mass

d_{ij} = distance

For example, for given sizes of two cities, P_i and P_j, and distance between them, the flow (l_{ij}) could be measured and the empirical constant determined. Future traffic could then be predicted on the basis of changes in size of the cities. This model does not take into account the availability of fuel; the cities could change in size but the flow decrease because of reductions in available fuel. Perhaps the above equation could be modified as follows:

$$l_{ij} = F \frac{(P_i P_j)}{(d_{ij})^m} E_i E_j$$

where E_i and E_j would represent energy available to transportation.

There is work here for fruitful research. Research on the role of transportation systems in maintaining high energy systems has been conducted by Walker (1976).

Integration of the INSA Program with Energetic Analysis

The ultimate aim of the Inland Waterway Navigation System Analysis (INSA) Program is to maximize the efficiency of the waterway system through predictive commodity flow models. Included in this system's program is a complete waterway monitoring system, an information system on boat traffic, and a file of cost/hour for different types of towboats and barge. Knowing or assuming a given set of demands, the inter-industry, inter-regional commodity flow models can predict the traffic flow, delay times, bottlenecks, and cost for alternative transportation modes from a modal split analysis. These include several parameters such as ton-miles moved, direct fuel consumed, capital costs of replacement, and operating and maintenance costs. Based on the traffic patterns, delay times, and bottlenecks generated by the model, improvements to the waterway system can be recommended.

Predicting the operation and maintenance costs, new capital investment and ton-miles transported is the first step toward completing a total energy analysis of a transportation system.

Figure 8 concisely summarizes how these system approaches might fit together for completing an energetic analysis of the barge transportation system. This diagram illustrates that once the detailed investments and costs are determined from the INSA model, then a total energy

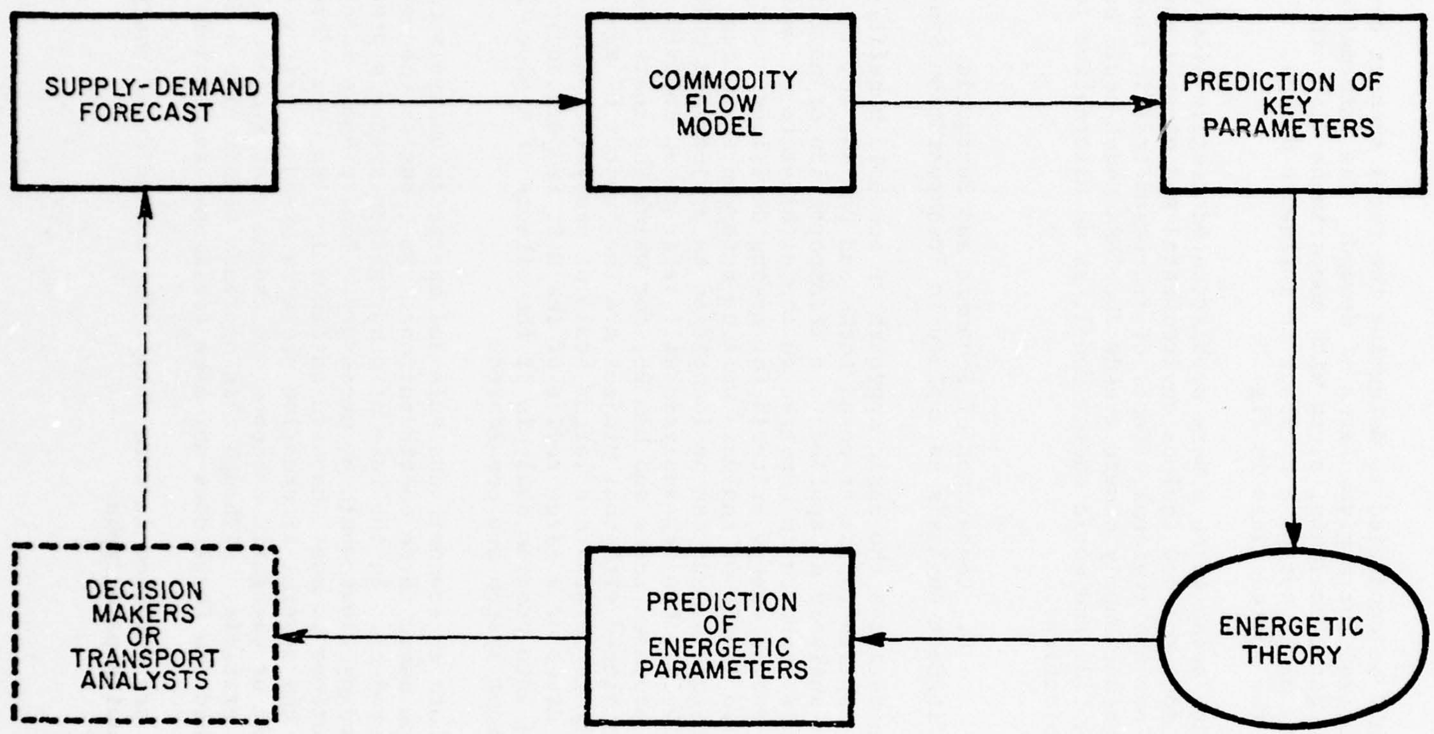


Figure 8. Schematic Diagram Illustrating How Energetic Analysis Might Fit into the Inland Waterway Systems Analysis Program.

analysis could be conducted to determine the total support energy per ton-mile required for a given level of demand. The information arising from the energetic analysis, along with comparisons with other forms of transport, might act as a feedback to influence demand. This is depicted by the dotted lines in Fig. 8.

The INSA model seems to be a very sophisticated traffic flow model. However, it does not now include environmental and natural energy considerations nor the regional effects of increased traffic flow. In order to forecast supply demand trends the INSA model could be interfaced with a U.S. and world energy model, as an alternative to relying on OBERS projections.

B. Comparison of Economic and Energetic Benefit/Cost Analysis as Applied to Transportation Systems

This section outlines the basic approach of economic benefit/cost analysis as applied to the proposed Locks and Dam No. 26, i.e., economic benefit/cost analysis as applied to a transportation or navigation project. This approach is compared to the alternative of using energy analysis to define energy criteria for making decisions about proposed projects. Two levels of analysis will be referred to during the following discussion and can be identified as project analysis and program analysis. Project analysis will refer to an individual project, such as the proposed Locks and Dam 26, for which the costs and benefits directly associated with that project are the subject of analysis. Program analysis refers to a larger scale of analysis, perhaps the whole Mississippi River or a large region of the U.S. Project analysis can easily merge into program analysis if the effects of a given project on the next larger system are considered.

Basically, both an economic analysis and energetic analysis consist of the following basic three considerations. One, assess the need for a particular project. In the case of a navigation system a prediction of future commodigy flows would be necessary. Two, propose alternative project solutions to meet the need outlined in step one. Three, assess or evaluate the several alternative projects based on criteria derived from economic or energetic concepts and choose that project which best meets these criteria. Although this approach sounds like a neat and concise method the Corps does not make decisions based solely on economics.

These steps are outlined in more detail for economic and energy analysis in the following paragraphs.

Economic Analysis

An assessment of the need for a particular project can be based on political or social concerns. In the case of the barge transportation system, the need is predicted on the likely future traffic demand for the system. Thus, the need is assessed by how accurately future demand can be predicted. The analysis on Locks and Dam No. 26 was done by the St. Louis District, Corps of Engineers. Low, medium, and high projections were made for many different commodities, but the assumption underlying the projections is that per capita energy use is going to increase at some percentage each year. Predictions of future economic growth and the transport of commodities is based on OBERS study and projections.

To meet the demand for projected future movement of barge traffic, several alternative solutions for providing varying degrees of capacity to Locks and Dam No. 26 were proposed by the St. Louis District Corps of Engineers. These varied from no capacity improvements to a new dam with increased capacity from the construction of two 1200-foot locks. An evaluation of these proposed alternatives was then made in economic terms using benefit/cost analysis. The first step is a definition of the benefits. For a project of regional nature the benefits might be defined as the income generated in the region as a result of the project. For a barge navigation project the benefits were computed by taking the rate differential (after suitable adjustment for inventory and delay costs) between shipments by water and the least costly alternative and applying this differential to the expected traffic levels utilizing the project. This is a benefit if there is a savings in transportation costs meaning lower prices for consumers. Benefits are calculated for each year of the life of the project, and these benefits discounted to present worth with a discount factor of 5 7/8%. Although the discount rate is set by Congress there is much debate as to what the value should be (Kelso, 1964; Haveman, 1965).

A small variation in the discount rate, especially for a long project life, can change the present worth of benefits significantly. The concept of discounting implies that money in the future is worth less than money in the present. This concept may need to be changed under a no-growth or steady state economy. The existence of limited resources may make the economic value of these resources more important in the future.

Other benefits attributed to the Locks and Dam No. 26 project included redevelopment benefits, attributed to increased employment in the local area, and the estimated annual recreation benefit in the area. The annual benefits for the project are discounted to present worth with the follwing formula:

$$PVB = \sum_{i=o}^{N} \frac{B_i}{(1+r)^i}$$

N = lifetime of project

r = discount rate

B_i = benefits in i^{th} year

PVB = present value of benefits

An annual cost for construction is calculated based on the initial cost and the life of the project. Annual operation and maintenance costs are added to this to obtain a total annual cost for the project in present worth dollars. A benefit/cost ratio is then obtained by dividing the annual transport benefits by the net annual cost. The net annual benefits can be calculated by subtracting the annual costs from the annual transport benefits.

The effects of a project on the environment or the natural systems is usually described in terms of physical effects, but a dollar value for environmental destruction is not usually assigned because of the difficulty of assigning economic value to natural system energies (this is discussed in section I.) This environmental damage is a definite cost, especially in the long run, a cost which perhaps should be given more value in the future and assigned a negative discount rate.

In the Locks and Dam No. 26 report an attempt was made to assess the socio-economic impact. An attempt was also made to predict the beneficial and adverse impacts on the immediate planning area and on the nation as a whole because of "multiplier" effects in the economy. However, no attempt was made to assess future impacts on the Mississippi River as a whole especially with regards to maintaining the river or the costs of deepening the river to a depth of 12 feet.

It is always difficult to determine the boundaries of a problem and how to account for secondary and feedback effects. For example, if the construction of Locks and Dam No. 26 does lead to a drastic change in the river because of dredging a 12 foot channel, there is the question if this project should be charged with environmental costs and energy costs of dredging. This is the problem with incremental analysis; that is, the consideration of one project at a time without calculations of the cumulative effects at the larger system level.

Energetic Analysis

As in the economic approach, in energetic analysis the identification of a need for a given project may be based on many considerations. However, from an energy viewpoint the anticipated need for a project would be based on energy criteria. For ecample, a good case can be made that the production of economic value is based on available energy, as described in detail in section II-A. Future economic growth can be predicted based on anticipated growth of energy consumption. Once some kind of future predictions are put forth then alternative projects can be proposed and evaluated.

As explained in section II-A, a total energy analysis can be performed for a given project to estimate the energy requirements of labor, goods, fuels, and natural energy disruption. These could be approximated on a yearly basis per ton-mile, and called energy/ton-mile, e_1. Likewise, the total direct and indirect energy required for the barge companies and Corps of Engineers per ton-mile can be estimated based on yearly requirements of labor, goods, and fuels, and likewise called energy/ton-mile, e_2. The total energy/ton-mile would then be $e_1 + e_2 = e_3$. Multiplying e_3 by the ton-miles shipped in a given year gives the energy required in that year. A similar calculation for an alternative transport such as rail would also produce an energy expenditure for the shipment of the same amount of goods. If the barge system used less energy, then there would be an energy savings in that year. This energy savings could presumably be used in some other part of the economy to increase economic value. An energy benefit/cost ratio for the project would be the average annual energy savings divided by the average annual energy cost of the project.

Minimizing the energy costs of transport maximizes the energy available to the general economy for the creation of economic value. This seems to be related to the maximum power principle discussed in section II-A. This maximum energy principle can also be used to evaluate the regional impacts of alternative projects by choosing that project which maximizes the total energy flow in the region and minimizes economic waste. Just as with economic analysis the defining of a region associated with a given project is rather arbitrary. However, choosing a region may be justified on political or economic cohesiveness. Since the total energy of a region is made up of both fossil fuel and natural energies, any development which takes place will affect both these energies. The system which maximizes the sum of these two energies should be the one which out-competes alternative ones. The situation of a transportation project and its associated region is diagrammed in Fig. 9. The transport system is shown to affect both fossil fuels going into a region and the natural energies of a region. Maximizing the energy flow to the region, J_2+J_3, while minimizing the energy required per unit of transport, J_1,

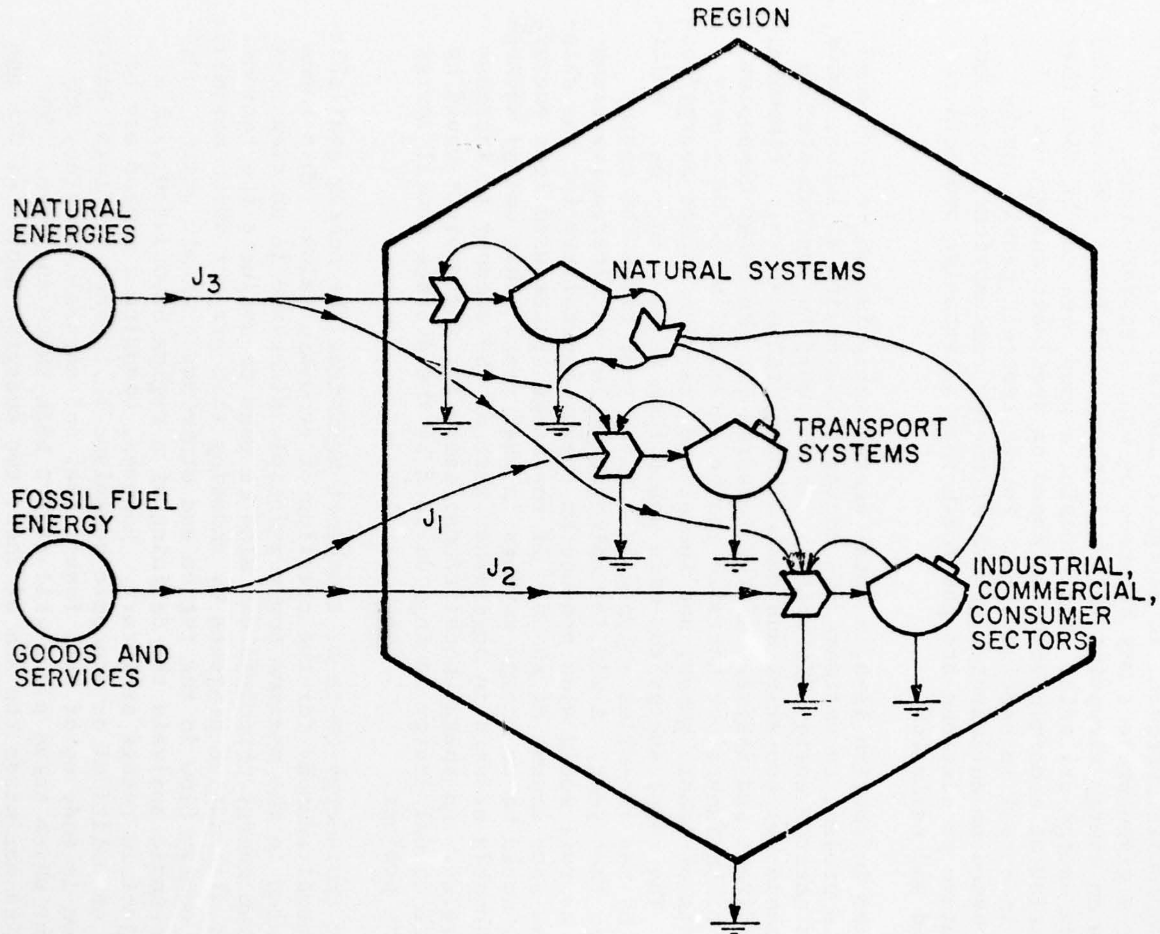


Figure 9. Simplified Diagram Showing the Energy Flows Associated with a Transportation System and a Surrounding Region.

are criteria which would maximize total energy and economic value.

In determining the value to the nation of a project such as Locks and Dam No. 26, energy value of imports and exports should be considered. As discussed in section II-A, if the energy value of imports is greater than that of exports, then a net energy value is flowing into the country. The trading of wheat for fuels is one example. How much energy value, if any, does this add to the regional or U.S. economy? (See page 28)

Analytical Comparison of Economic and Energetic Benefit/Cost Analysis

For economic analysis the present value of benefits and costs is calculated as follows:

$$pvC = \sum_{i=o}^{N} \frac{O_i}{(1+r)^i} + K$$

$$pvB = \sum_{i=o}^{N} \frac{B_i}{(1+r)^i}$$

pvC = present value of total cost of a project

pvB = present value of total benefits of a project

O_i = annual operation, maintenance, and replacement costs

N = life of project in years

r = discount rate

B_i = annual benefits

K = initial construction cost

For a transportation project the benefits are defined as the savings in costs for shipping compared to the least costly alternative. Thus,

$$B_i = (S_{1i} - S_{2i}) \times T_i \times M_i = \Delta S_i \times T_i \times M_j$$

S_{1i} = rate per ton-mile in i^{th} year, for next least costly alternative transportation mode.

S_{2i} = rate per ton-mile in i^{th} year for transport system being evaluated

T_i = tons shipped in i^{th} year

M_i = total shipping distances in i^{th} year

ΔS_i = rate differential in i^{th} year

For simplicity, if it is assumed that costs, benefits, and rates remain the same in each year, then

O_i = 0 costs per year

$B_i = B = \Delta S \times T \times M$ = annual benefits

then

$$pvC = O \times \sum_{i=o}^{N} \frac{1}{(1+r)^i} + K$$

$$pvB = B \times \sum_{i=o}^{N} \frac{1}{(1+r)^i} = \Delta S \times T \times M \times \sum_{i=o}^{N} \frac{1}{(1+r)^i}$$

The yearly net economic benefits are then

$$\frac{pvB}{N} - \frac{pvC}{N} = (\Delta S \times T \times M \times \frac{1}{N} - \frac{O}{N}) \sum_{i=o}^{N} \frac{1}{(1+r)^i} - \frac{K}{N}$$

An energy analysis determines the benefits and costs with the following formulas

$$pVE_c = \sum_{i=o}^{N} E_{oi} + E_k + E_n$$

$$pVE_B = \sum_{i=o}^{N} E_{Bi} = \sum_{i=o}^{N} \Delta e_i \times T_i \times M_i$$

pvE_c = present value of energy costs

pvE_B = present values of energy benefits or savings

E_{oi} = annual operation, maintenance and replacement costs

E_k = energy cost of initial construction

E_n = natural energy losses due to natural system destruction

pvE_B = present value of energy savings

E_{Bi} = annual energy savings

Δe_i = difference in fuel consumption for next least costly transport mode and system under study per ton-mile for i^{th} year

T_i = tons shipped in i^{th} year

M_i = total shipping distances in i^{th} year

where all energies are expressed in fossil fuel equivalents. For simplicity assume that annual values are constant so that

$$pvE_c = NE_o + E_k + E_n$$

$$pvE_B = NE_B = N\Delta e \times T \times M$$

and the net annual savings are

$$\frac{pvE_B}{N} - \frac{pvE_c}{N} = \Delta e \times T \times M - (E_o + \frac{E_k}{N} + \frac{E_n}{N})$$

Now, if these energy values must be obtained from economic data and converted to energy data, the general formula for costs and benefits will be

$$pvE_c = \sum_{i=o}^{N} O_i R_{oi} + KR_k + E_n$$

$$pvE_B = \sum_{i=o}^{N} \Delta S_i R_{si} \times T_i \times M_i$$

where R_{oi} = energy/dollar ratio for operation and maintenance in i^{th} year

R_k = energy/dollar ratio for construction

R_{si} = energy/dollar ratio for general economy

As explained in section II-A the energy/dollar ratios are decreasing with time, while annual operating expenses are increasing because of inflation. There is evidence that the general energy to dollar ratio is decreasing at the same rate as inflation is increasing. The energetic analysis differs from the dollar analysis in three ways:

1) It is not known whether energy should be discounted and, if so, at what rate.

2) The energy/dollar ratios are different depending on the dollar flow under consideration (e.g., $R_{oi} \neq R_{si}$).

3) The inclusion of natural energies, E_n, in the energy analysis differs from the economic approach.

If it is assumed that the energy/dollar ratios are declining at the same rate as inflation, then

$$R_{o1} = R_{o1}(1-d)^i$$

where R_{o1} is the energy/dollar ratio in the base year and d is the inflation rate. Furthermore, assume that all the energy/dollar ratios are the same so that

$$R = R_{o1} = R_k = R_{si}$$

and that the annual costs are constant so that the equations for energy costs and benefits can be written as

$$pvE_c = R \times O \sum_{i=o}^{N} (1-d)^i + K \times R + E_n$$

$$pvE_B = \Delta S \times R \times T \times M \sum_{i=o}^{N} (1-d)^i$$

The net energy yearly benefits are then

$$I_1 = \frac{pvE_B}{N} - \frac{pvE_c}{N} = (\Delta S \times T \times M \times \frac{1}{N} - \frac{O}{N}) \times R \times \sum_{i=o}^{N} (1-d)^i - \frac{K}{N} \times R - \frac{E_n}{N}$$

From a previous paragraph the net economic benefits are given by

$$I_2 = \frac{pvB}{N} - \frac{pvC}{N} = (\Delta S \times T \times M \times \frac{1}{N} - \frac{O}{N}) \times R \times \sum_{i=o}^{N} \frac{1}{(1+r)^i} - \frac{K}{N}$$

The above two expressions differ by the terms

$$\sum_{i=o}^{N} (1-d)^i; \quad \sum_{i=o}^{N} \frac{1}{(1+r)^i}; \quad \frac{E_n}{N}$$

Under certain circumstances

$$(1-d)^i \simeq 1-di \quad \text{and} \quad \frac{1}{(1+r)^i} \simeq 1-ri$$

so that $\sum_{i=o}^{N} (1-d)^i \simeq \sum_{i=o}^{N} (1-di)$

$$\sum_{i=o}^{N} \frac{1}{(1+r)^i} \simeq \sum_{i=o}^{N} (1-ri)$$

If it is assumed that the inflation rate, d, equals the discount rate, r, then the above two summations are equal. The relationship between net energy benefits and net economic benefits becomes

$$I_1 = I_2 - \frac{E_n}{N}$$

and the difference in analysis will show up by the magnitude of the natural energy losses, $\frac{E_n}{N}$

Assumptions in the above analysis include:

1) assumption of constant energy/dollar ratios for the specific years

2) inflation rate = discount rate

3) restrictions on r, d, and N(lifetime) so that summations could be simply approximated

4) constant yearly operation costs and benefits

In general, economic and energetic benefit/cost analysis differ, the differences residing in the variation of energy/dollar ratios over time, the inflation and discount rates, and the natural energy losses.

C. Energy Analysis Procedure

This section outlines the steps that might be taken in conducting an energy analysis. These are as follows:

1. Identify the Scope of the Analysis - The object of the study must be chosen. The analysis may range from a single object, such as a particular good, to a large scale system, which might include anything from a particular transportation system or industry to a natural ecosystem.

2. Identify the Boundaries of the System - In the definition of the scope of the problem, the question of boundaries automatically arises. For example, if one analyzes a transportation system, one must decide what will be included as part of the system. Once the major components are identified then the major flows into, out of, and within the system can be identified. There is no one method of systematically representing the relationships between the flows and components of a system. This will depend on the object of the study. In general, when evaluating a system the modeler must consider the next larger system to obtain a realistic evaluation of the constraints and interdependencies.

3. Model Representation - Develop a model showing the main components, flows, and interactions. This report uses the symbolic language of H.T. Odum (1971), the symbols of which are shown in Fig. 1. Symbolic languages are excellent for organizing a system study, identifying major components and flows, and stimulating questions and further considerations. The language is also useful for mathematical simulation since a differential equation can be written for each storage (state variable) which expresses that the time rate of change of the storages is equal to its inputs minus outputs.

4. Assign Energy Value to Flows and Components - In general, any system in the economy requires inputs of capital (goods), services (labor), and natural systems (land, natural systems, or externalities). In particular, the major flows to be considered for a transportation system are capital investment, direct fuels, labor, government subsidies, natural energy subsidies, natural energy disruption, and energy value of goods shipped. An energy value should be assigned to these flows as outlined in section II-A. All energies should be put into equivalent units of energy with the use of energy quality factors. For examples of some energy calculations see sections III-A to III-D and Appendices I, II, and III.

5. Type of Analysis - There are basically two types of analysis that can be performed:

a. Static Analysis - This would consist of calculating the energy flows for a given year and a given level of demand. This information could then be used to calculate the total energy required per ton-mile shipped, the ratio of energy invested to energy delivered, the net energy of transport, or any other energy parameter of interest.

b. Dynamic Analysis - This type of analysis involves mathematical simulation in order to observe the behavior of the system through time. The dynamic analysis would consist of first-order, non-linear differential equations of the form:

$$\frac{dQ_i}{dt} = f\ (Q_1, \ldots, Q_N, I, \ldots I_m) \quad i = 1, 2, \ldots M$$

where Q_i = components or state variables of the system

$I_i, \ldots I_m$ = exogenous variables or outside forcing functions such as energy, capital, prices

The object of dynamic analysis is to see how the mathematical model representing the system responds to changes in parameters of interest. These parameters could be fossil fuel flows, prices of fuels, level of demand, energy costs of labor, etc. See section IV for illustration of a simulation model for the Northern Great Plains.

6. Interpretation of Analysis - The results of the analysis are interpreted to identify trends and gain understanding. Data needs or research required for greater understanding can be identified, and suggestions and policy formulations can be presented to decision makers.

CHAPTER III
SUBMODELS FOR TRANSPORTATION SYSTEMS

A. Energetic Analysis of Barge Transportation

Macro Analysis of the Inland Waterway System

Consider a barge transportation system such as the Inland Waterway System. Fig. 10 depicts the major elements associated with the barge system in its simplest form. The many hundreds of barge companies have been aggregated into one category and the Corps of Engineers into another, while the natural systems have been identified as the third major portion associated with the barge system. The storages Q_1 and Q_3 represent total capital structure assets of the barge companies and the Corps of Engineers, respectively. Deterioration of these two storages occurs because of deterioration of the equipment and is shown to be a function of the quantity of goods shipped. Both the barge companies and the Corps of Engineers are shown to have storages of money (Q_2 and Q_4) into which money flows from sales and government subsidies and from which money flows for the purchase of capital, labor, and fuels. Maintenance energies (J_2 and J_7) in the form of goods and services, operating energies in the form of fuels and labor (J_3 and J_6), and capital investment (J_1 and J_8) for expansion and replacement are required for system operation. The biomass storage of the riverine and associated terrestrial systems is represented by Q_5, with a loss of storage due to transportation stress represented by J_{11}. For the sake of completeness, the energies of loading and unloading are included as J_{13} and J_{14}. When making energy cost comparisons to other systems it should be stipulated whether loading and unloading costs are included. As explained in previous sections, an energy value may be assigned to each of these flows to approximate indirect and direct energy costs. Either energy/dollar conversion factors (see Table 3) or detailed energy pathway analysis of indirect energy flows (see Appendix I) could be used to assign energy values to the input flows.

A crude approximation to the energy requirements of the Inland Waterway System is presented in Fig. 11. The dollar values for operation and maintenance of the Corps of Engineers and the barge companies were converted to energy units by an average energy/dollar conversion factor for the economy. The potential and kinetic energies associated with the Mississippi River system were calculated from water flow characteristics. See footnotes to Fig. 11 for explanation of the calculations involved in Fig. 11.

In order to perform a more accurate analysis of the system, more detailed information on capital investment, labor, and fuels would be needed for a given year. This information could be in the form of dollar costs. For

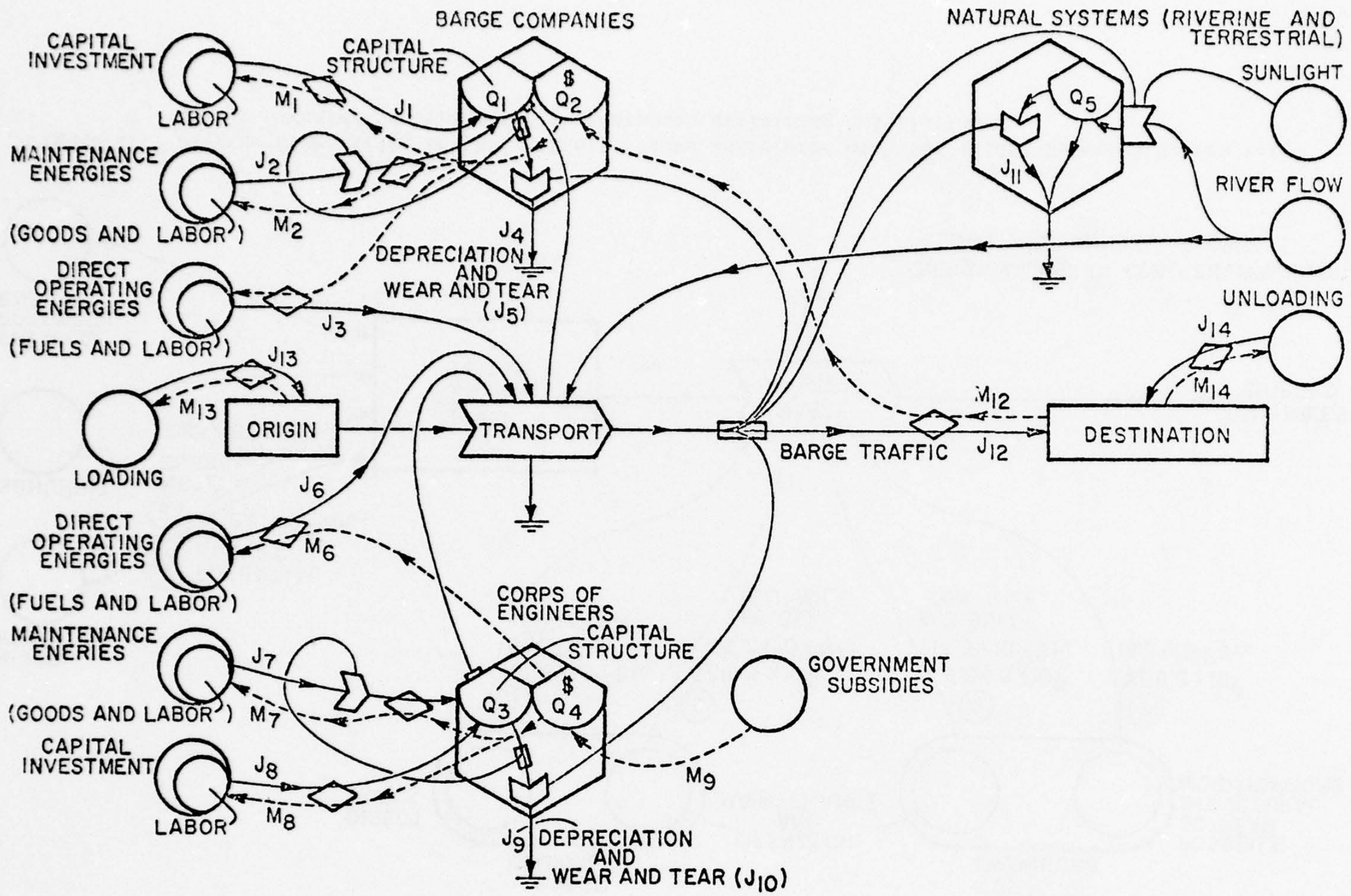


Figure 10. Major Components, Flows, and Interactions Associated with a Barge Transportation System Delivering Goods between One Origin and One Destination.

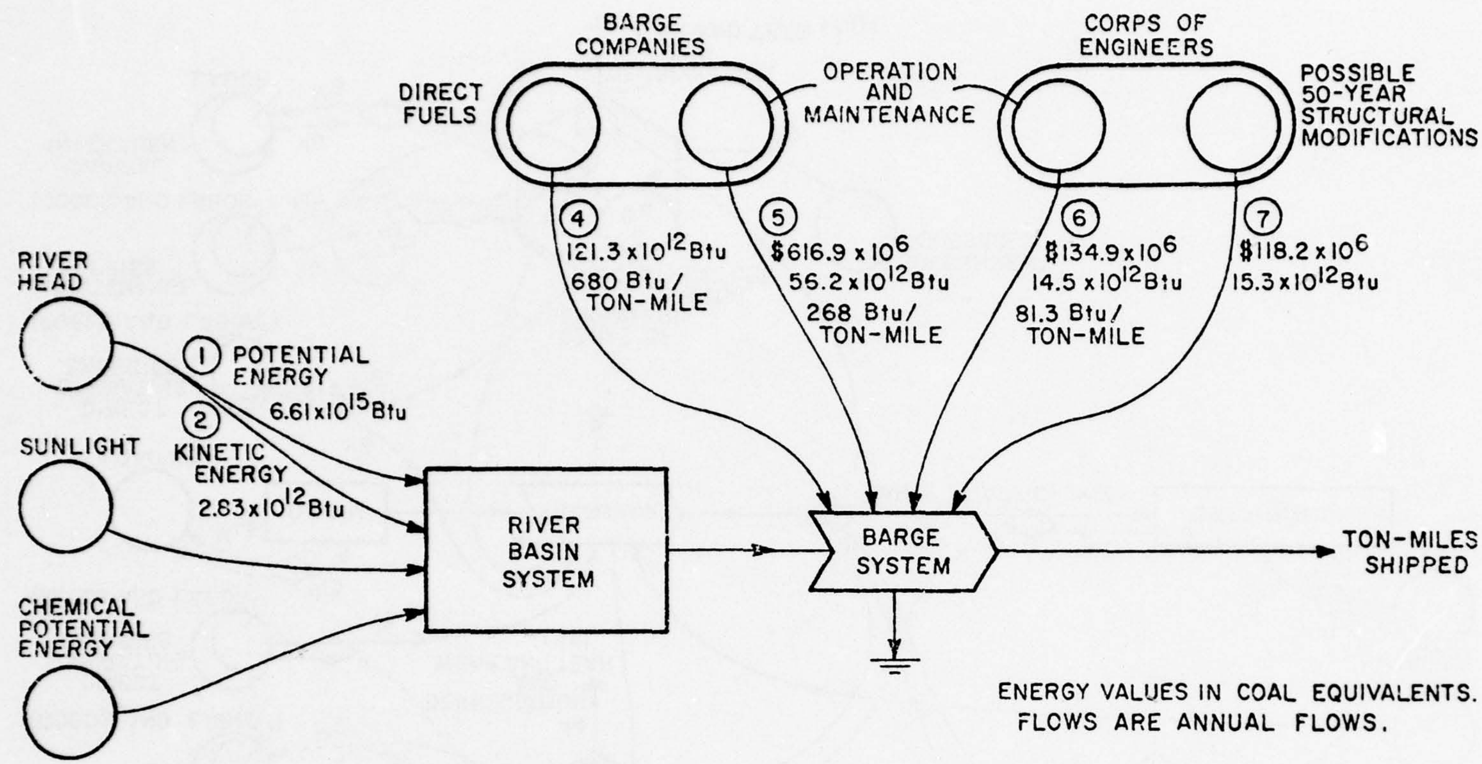


Figure 11. Diagram Summarizing the Major Energy Flows Associated with the Inland Waterway System for 1972. Circuled numbers refer to footnotes explaining calculations.

Footnotes to Figure 11

1. The rainfall associated with the Mississippi and its tributaries ranges from 20 to 60 inches/yr. (Water Atlas of the U.S., 1973). The area of drainage is approximately 1.25 million square miles (Lauff, 1967). The average elevation of cities on the Mississippi River and its tributaries was approximated to be 442 ft. The potential energy per cubic cm. of water is:

$$e = 1gh = 1gm/1cm^3 \times 980\ cm/sec^2 \times 442\ ft \times 30.48\ cm/ft$$

$$e = 1.32 \times 10^7\ ergs/cm^3$$

Volume of rainfall is approximately:

$$Volume = 40\ in/yr \times 2.54\ cm/in \times 1.25 \times 10^6\ miles^2 \times \frac{(5280\ ft)^2}{mile^2} \times \frac{(30.48)^2 cm^2}{ft^2}$$

$$Volume = 3.289 \times 10^{18}\ cm^3/yr$$

Total potential energy is

$$Potential\ energy = e \times Volume = 1.32 \times 10^7\ erg/cm^3 \times 4.34 \times 10^{25}\ cm^3$$

$$= 4.34 \times 10^{25}\ ergs/yr = 4.1 \times 10^{15} BTU/yr$$

Dividing by 0.62 to obtain energy in fossil fuel work equivalents (see Table 2) gives 6.6×10^{15}BTU/yr.

The potential energy of water in the river basin can be thought of as a natural energy subsidy. This energy input creates the river system which can be used by man for transportation.

2. The energy of the river can be interpreted as an energy subsidy to the Inland Waterway System. An approximate value for the total kinetic energy of the Mississippi River system can be calculated from average measurements at New Orleans. The average discharge at this point is approximately 620,000 cfs (Lauff, 1967) and the mean velocity is about 6 ft/sec (Reid and Wood, 1967). The average total kinetic energy/yr is

$$Kinetic\ Energy = \frac{62.4\ lbm/ft^3}{32.17\ lbm/slug} \times \frac{0.62 \times 10^6 ft^3}{sec} \times \frac{31.536 \times 10^6\ sec}{yr} \times 36\frac{ft^2}{sec^2}$$

Footnotes to Figure 11 (cont.)

$$K.E. = 1365.3 \times 10^{12} \text{ ft-lb}$$

$$K.E. = 1.76 \times 10^{12} \text{BTU} \times \frac{1 \text{ BTU (FFCE)}}{0.62 \text{ BTU K.E.}} = 2.83 \times 10^{12} \text{BTU (FFCE)}$$

The ton-miles shipped on the Inland Waterway System were approximately 178.4×10^9 in 1972 (Waterborne Commerce Statistics Center, Dept. of the Army). On a ton-mile basis the river subsidy for 1972 is approximately

$$\frac{2.83 \times 10^{12} \text{BTU}}{178.4 \times 10^9 \text{ ton-miles}} = 15.86 \text{BTU/ton-mile}$$

It was assumed that elevated water has an energy quality factor of 0.62 (see Table 2).

3. This flow represents natural system destruction due to navigation and could be calculated by knowing the loss of photosynthetic productivity in the riverine and terrestrial ecosystems due to navigational modifications.

4. Approximately 680 BTU's/ton-mile (Hirst, 1973).

5. Operating expenses have been estimated by A.T. Kearney, Inc. (1974) to be anywhere from 83.2% to 90.1% of revenue. Total revenue was estimated to be \$712,000,000 for 1971 and total ton miles at 210 billion. Taking an average operating percentage as 86.65% of revenue gives \$616.9 million in operating expenses. An approximate energy to dollar ratio of 91,140 BTU/\$ for 1971 (see Table 3) gives an energy cost of

$$\frac{0.8665 \times \$712 \times 10^6 \times 91140 \text{ BTU/\$}}{210 \times 10^9 \text{ ton-miles}} = 268 \text{ BTU/ton-mile}$$

6. Operation and maintenance energies for 1972 are approximated as \$134.93 million (Sharp, 1976). Assume 50% is labor and 50% is materials (Sharp, 1976). Energy ratio for labor is 85752 BTU/\$ (see Table 3); energy ratio for materials is 129,128 BTU/\$ (see Appendix III). Energy cost is

$$\$67.49 \times 10^6 \times 85752 \text{ BTU/\$} + \$67.49 \times 10^6 \times 129{,}128 \text{ BTU/\$}$$

$$= 1.45 \times 10^{13} \text{ BTU}$$

On a ton-mile basis for 1972 the energy cost is (see note 3)

Footnotes to Figure 11 (cont.)

$$\frac{14.5 \times 10^{12} \text{ BTU}}{178.4 \times 10^{9} \text{ ton-miles}} = 81.3 \text{ BTU/ton-mile}$$

7. INSA Group (Sharp, 1976) estimates possible 50-yr modifications to amount to $\$5909.7 \times 10^6$. This amounts to an energy cost per year of (see Appendix III for energy/dollar ratio)

$$\frac{1}{50} \times \$5909.7 \times 10^{6} \times 129128 \text{ BTU/\$} = 1.53 \times 10^{13} \text{ BTU/yr}$$

materials and capital it could be in the form of number and types of equipment. Information for the following categories would be needed in a given year:

1. Barges
2. Towboats
3. Locks and dams
4. Barge company capital stock and investment
5. Corps of Engineers capital stock and investment
6. Dredging activities
7. Fuel consumption by towboats and other machinery
8. Labor costs
9. River energy
10. Natural system energy disruptions
11. Maintenance activities

Detailed environmental studies would also be necessary to determine natural energy losses. Once all the flows for a given year and the ton-miles shipped are determined, then a total energy/ton-mile factor can be calculated from the following formula:

$$(\text{total energy inputs} + \text{natural energy losses}) \div (\text{ton-miles})$$

As described in previous sections and paragraphs, there are basically two ways to approximate the indirect energy costs associated with capital and labor inputs. Typical pieces of equipment could be looked at and energy flows determined. For example, barge companies invest mainly in barges and towboats and the Corps of Engineers capital construction is tied up with locks and dams. Appendices I and II show calculations which estimate the total energy necessary (as far back as the raw materials) for building a typical barge (195' x 35') or towboat (5,000 hp). Dividing these energies by the lifetime of the equipment gives an approximate energy investment per year for this equipment. Multiplying this by the number of barges and towboats built in a year would give an approximate capital investment energy input. Knowing the prices of this equipment allows calculations of energy to dollar ratios for each type of equipment, so that energy cost of a piece of equipment could be determined from its dollar cost. Ideally the energy cost or energy to dollar ratios could be determined for all categories of barges, towboats, locks and dams, etc. to allow accurate energy analysis. Appendix III shows calculations for the energy cost of Locks and Dam number 26 replacement. Table 4 presents some energy to dollar ratios calculated for the barge system.

In the absence of the detailed information above, the energy to dollar ratios for the input-output sectors of the U.S. economy (Herendeen and Bullard, 1974) could be used for approximation. These ratios would have to be corrected to account for natural energy subsidies (see section II-A).

Table 4

Approximate Energy/Dollar Ratios for Several Categories Associated with Barge Transportation

Category	BTU/Dollar Ratio
Barges (1975)	179767
Towboats (1975)	98480
Proposed Locks and Dam #26 (1975)	129128
Labor (1974)	74426[d]
Average for Economy (1974)	74426[d]

[a]See Appendix I.

[b]See Appendix II.

[c]See Appendix III.

[d]See Table 3 which gives 18,700 kcal/$ for 1974. Since 1 kcal = 3.98 BTU the ratio is 74426 BTU/$.

As listed in Table 4 and explained in section II-A, the energy to dollar ratio for labor is taken as the average for the economy.

In summary, the annual energy cost for the various flows depicted in Fig. 10 could be determined with the methods outlined above. The total energy cost in a given year, including loading and unloading, would then be given by:

$$TE = \text{Total Energy} = J_1 + J_2 + J_3 + J_6 + J_7 + J_8 + J_{11} + J_{13} + J_{14}$$

Knowing the total ton-miles, TM, shipped in a given year allows the total energy per ton-mile to be calculated. Table 5 summarizes the energy costs associated with the barge system including the Corps of Engineers and the barge companies.

Analysis of a Barge Tow on the Upper Mississippi

The following section calculates the energy costs associated with a 5600 H.P. towboat handling a 15 jumbo barge tow between St. Louis, Missouri, and St. Paul, Minnesota. The round trip is approximately 1318 miles and takes about 14 days. The energy costs for this trip are summarized in Table 6 with footnotes detailing the calculations.

If the numbers in Table 6 provided by Federal Barge Lines are compared to overall data for the barge system shown in Fig. 11, one can see that the particular information provided in Table 6 represents a particularly efficient tow. The direct fuel cost of 249 BTU/ton-mile is much more favorable than Hirst's (1973) published value of 680 BTU/ton-mile or Barloon's (1972) value of 457 BTU/ton-mile.

Energy Analysis of Coal Transport by Barge

As mentioned in other sections the energy cost of transporting coal is of increasing interest because of the recent energy shortages experienced in the U.S. As a typical case it will be assumed that a tow with 15 jumbo barges is used and that the distance travelled is 1,000 miles. This distance was chosen as a basis of comparison with the analysis of railroads, pipelines, and transmission lines contained in sections III-B to III-D. One thousand miles is the approximate distance from the Northern Great Plains to a major city on the Mississippi River. The energy cost per ton-mile calculated in previous sections and summarized in Fig. 11 and Table 6 were used to calculate the energy cost for transporting coal a thousand miles. The numbers in Fig. 11 represent average or typical barge system data, while the data presented in Table 6 represent an unusually efficient case. For the purposes of this section it will be assumed that this efficient case is representative of a dedicated coal barge tow. The results of calculations using energy costs for "average" conditions and "dedicated" tow conditions are summarized in Table 7.

Table 5

Approximate Energy Costs for Inland Waterway System[a]

	Total Energy, 10^{12} BTU	Energy/Ton-Mile BTU/Ton-Mile
Direct Energy	121.3	680
Corps of Engineers: Operation and Maintenance	14.5	81.3
Barge Companies: Operation and Maintenance	56.2	268
TOTAL COSTS		1029.3 BTU/ Ton-Mile

[a]See Fig. 11 and its footnotes for explanation of the calculations. All energy values are in fossil fuel equivalents. Values for 1971-72. Natural energy destruction is not included.

Table 6

Costs of a 14-day Trip for a 5600 H.P. Towboat with 15 Jumbo Barge Tow [a]

Category	Dollar Cost	Energy Cost (10^6 BTU)	BTU/ton-mile
Fuel Oil[b]		7640.	249
Towboat Maintenance[c]	1380.8	111.7	3.64
Barge Maintenance[d]	1783.6	161.2	5.25
Labor[e]	15050.	1120.	36.5
Barge Accidents[f]	406.6	73.09	2.38
Repairs[g]	604.1	44.96	1.47
Capital Investment			
Barges[h]	1956.2	351.6	11.5
Towboat[i]	1956.2	192.6	6.28
Corps of Engineers, O. & M.	23204.3	2494.3	81.3
TOTAL COST	46341.8	12189.45	397.32

[a]Data obtained from Federal Barge Lines, Inc. (St. Louis, Missouri) for a 5600 H.P. towboat with 15 jumbo barges travelling between St. Louis and St. Paul (roundtrip approximately 1318 miles).

[b]Approximately 3640 gallons of fuel oil/day. For 14 days this is a fuel consumption of 50960 gallons or 50960 gal. x 0.15 x 10^6BTU/gal = 7.64 x 10^9BTU. Tow consists of 6 jumbo semi-integrated barges:
6 x 1630 tons = 9780 tons and 9 jumbo box barges: 9 x 1500 tons = 13500 tons.
Total tons = 23280 tons
Total miles is 1318 miles so that ton-miles is 1.318 x 10^3 x 23.28 x 10^3 or approximately 30.68 x 10^6 ton-miles.
Fuel oil/ton-mile is 7.64 x 10^9 BTU/30.68 x 10^6 ton-miles or 249 BTU/ton-mile.

Footnotes for Table 6 (cont.)

[c] Annual towboat maintenance is approximately \$36,000 (75% labor; 25% main engine parts). For a 14-day trip the energy costs are approximately:

$$\text{Labor: } 0.75\frac{14}{365} \times \$36,200 \times \frac{74,426 \text{ BTU}}{\text{Dollar}} = 77.5 \times 10^6 \text{ BTU}$$

$$\text{Engine Parts: } 0.25 \times \frac{14}{365} \times \$36,200 \ \frac{98,480 \text{ BTU}}{\text{Dollar}} = 34.18 \times 10^6 \text{ BTU}$$

(See Table 4 for energy/dollar ratios).

$$\text{Towboat Maintenance Costs} = \frac{(77.5 + 34.18) \times 10^6 \text{ BTU}}{30.68 \times 10^6 \text{ ton-miles}} = 3.64 \text{ BTU/ton-mile}$$

[d] Barge maintenance is approximately \$3100/year (85% labor; 15% steel). For a 15 barge tow this is \$46,569/tow/year.

$$\text{Labor: } 0.85 \ \frac{14}{365} \ \$46,569 \ \frac{74,426 \text{ BTU}}{\text{Dollar}} = 113 \times 10^6 \text{ BTU}$$

$$\text{Steel: } 0.15 \ \frac{14}{365} \ \$46,569 \ \frac{179,767 \text{ BTU}}{\text{Dollar}} = 48.2 \times 10^6 \text{ BTU}$$

(See Table 4 for energy/dollar ratios).

$$\text{Tow Maintenance Costs} = \frac{(113 + 48.2) \times 10^6 \text{ BTU}}{30.68 \times 10^6 \text{ ton-miles}} = 5.25 \text{ BTU/ton-mile}$$

[e] Labor costs for a towboat are approximately \$1075/day. For a 14-day trip:

$$\$14(1075) \times \frac{74,426 \text{ BTU}}{\text{Dollar}} = 1120 \times 10^6 \text{ BTU}$$

$$\frac{1120 \times 10^6 \text{ BTU}}{30.68 \times 10^6 \text{ ton-miles}} = 36.5 \text{ BTU/ton-mile}$$

[f] Barge accidents are approximately \$10600/year. For 14 days this is:

$$\frac{14}{365} \times (10,600) \ \frac{179,767 \text{ BTU}}{\text{Dollar}} = 73.09 \times 10^6 \text{ BTU}$$

$$\text{or } \frac{73.09 \times 10^6 \text{ BTU}}{30.68 \times 10^6 \text{ ton-miles}} = 2.38 \text{ BTU/ton-mile}$$

Footnotes to Table 6 (cont.)

[g]Barge repair is approximately \$1050/barge/year. For a 15 barge tow this is \$15750/tow/year. For 14 days:

$$\frac{14}{365} \times (\$15{,}750)\ \frac{74426\ \text{BTU}}{\text{Dollar}} = 44.96 \times 10^6\ \text{BTU}$$

$$\text{or } \frac{48.3 \times 10^6\ \text{BTU}}{30.68 \times 10^6\ \text{ton-mile}} = 1.47\ \text{BTU/ton-mile}$$

[h]The total fossil fuel energy that goes into a barge is approximately 13648×10^6 BTU (See Appendix I). Assuming a 25 year lifetime this is 545.9×10^6 BTU/yr. The natural energy portion contributing to the value of the barge is the cost of the goods multiplied by the natural energy to dollar ratio for the year 1974 (see Appendix I and Table 3). This is \$85,000 x 19,200 BTU/\$ = 1632×10^6 BTU or 65.3×10^6 BTU/yr

The total energy cost is then $(545.9 + 65.3) \times 10^6$ BTU/yr = 611.12×10^6 BTU/yr.

For 14 days and 15 barges the energy cost is $\frac{14}{365} \times 15 \times 611.2 \times 10^6$ BTU $= 351.6 \times 10^6$ BTU

On a ton-mile basis this is $\frac{351.6 \times 10^6\ \text{BTU}}{30.68 \times 10^6\ \text{ton-miles}} = 11.5$ BTU/ton-mile

[i]The energy cost to build a 5000 H.P. boat is $80{,}866 \times 10^6$ BTU and the natural energy contribution is $\$1.02 \times 10^6 \times 19{,}200$ BTU/\$ = $19{,}584 \times 10^6$ BTU.

The total cost is thus $(80{,}866 + 19{,}584) \times 10^6$ BTU - $100{,}450 \times 10^6$ BTU. (See Appendix II and footnote h). For a 20 yr lifetime and 14 days use the energy cost is:

$$\frac{14}{365} \times \frac{1}{20} \times (100450 \times 10^6)\ \text{BTU} = 192.6 \times 10^6\ \text{BTU}$$

On a ton-mile basis this is:

$$\frac{192.6 \times 10^6\ \text{BTU}}{30.68 \times 10^6\ \text{ton-miles}} = 6.28\ \text{BTU/ton-mile}$$

[j]See footnote 6 to Figure 11. Dollar cost per ton-mile for Corps of Engineers is $\$134.93 \times 10^6/176.4 \times 10^9$ ton-miles = $\$7.56 \times 10^{-4}$ ton-mile. Cost of barge tow is $\$7.56 \times 10^{-4} \times 30.68 \times 10^6$ ton-miles = \$23,204.

Table 7

Energy Costs, Yield Ratio and Net Energy of Coal Transported by a 15 Jumbo Barge Tow For a Distance of 1,000 Miles[a]

	Yield Ratio, Y $Y = \frac{\text{Energy Transported}}{\text{Transport Cost}}$	Net Energy = Energy Transported - Transport Cost (BTU)
Average Conditions[b]	19.4[c]	4.42×10^{11} [d]
Dedicated Tow Conditions[e]	50.4[f]	4.57×10^{11} [g]

[a]A 15 jumbo barge tow can carry 23,280 tons (see Table 6, footnote b).

[b]This represents average energy cost conditions for the barge system as outlined in Fig. 11.

[c]Tons transported is 23,280 (see footnote a). Assume energy value of coal is 10,000 BTU/lb = 20×10^6 BTU/ton.

Energy Transported = $23,280 \times 20 \times 10^6$ BTU

Energy Transported = 4.66×10^{11} BTU

Energy costs are 1029.3 BTU/ton-mile x 23,280 tons x 1,000 miles = 2.4×10^{10} BTU (see Table 5).

$$\text{Yield Ratio} = \frac{4.66 \times 10^{11}\ \text{BTU}}{2.4 \times 10^{10}\ \text{BTU}} = 19.4$$

[d]See footnote c.

$$\text{Net Energy} = 4.66 \times 10^{11}\ \text{BTU} - 2.4 \times 10^{10}\ \text{BTU} = 4.42 \times 10^{11}\ \text{BTU}$$

[e]Dedicated tow refers to barges reserved for coal. Federal Barge Lines data are an example. Data from Table 6.

[f]Energy transported = 4.66×10^{11} BTU (see footnote c). Energy cost is 397.32 BTU/ton-mile x 23,280 tons x 1,000 miles = 9.25×10^9 (see Table 6).

$$\text{Yield Ratio} = \frac{4.66 \times 10^{11}}{9.25 \times 10^{9}} = 50.4$$

[g]Net energy = 4.66×10^{11} BTU - 9.25×10^9 BTU

Net energy = 4.57×10^{11} BTU

Energy Subsidy From Nature to River Transportation Systems

1. Calculations of energy subsidy from nature to river transport. The energetics approach is better suited to quantify the contributions from nature than is an economic approach. The river transportation system developed due to configurations of the terrain, the river basin, and river flow. These are subsidies from the natural environment that are contributed to man. Other transportation systems, rail, and pipeline must prepare the terrain and do not have the free subsidy of river channel and flow.

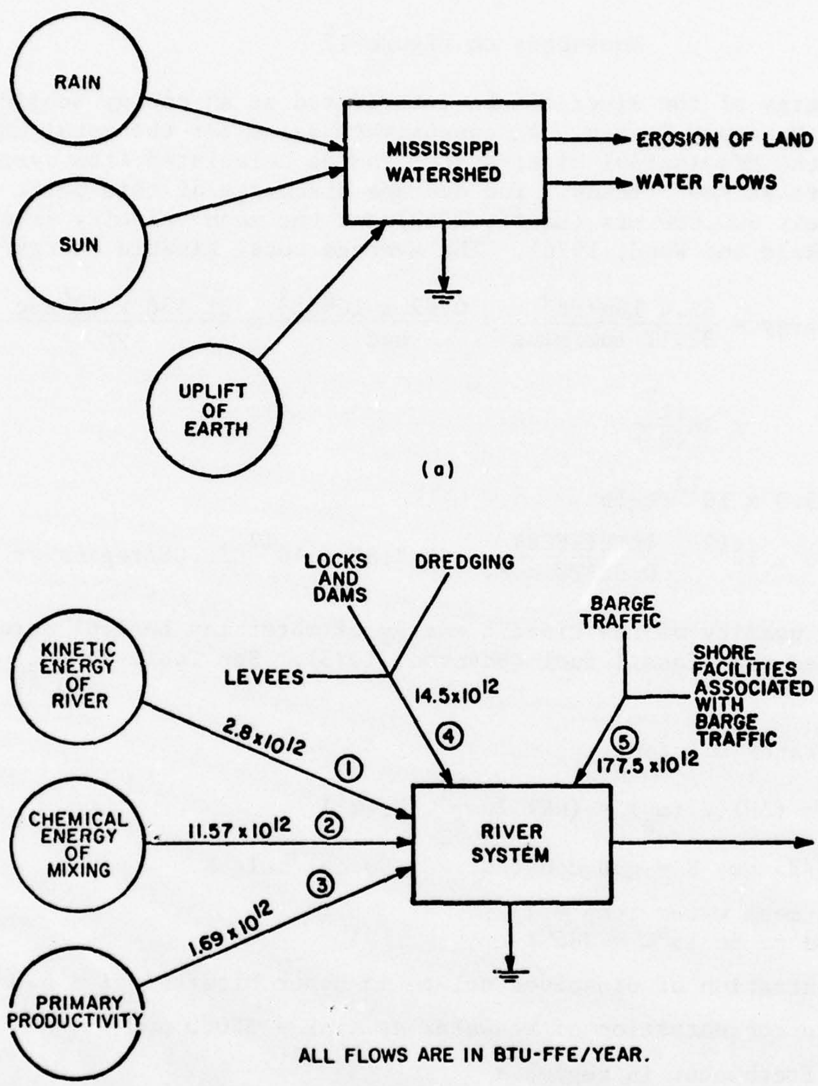
There are several possible ways of calculating the free subsidy from nature, the subsidy that makes a basin and a river of sufficient flow for men to use. On the large scale the Mississippi Basin is formed by a balance of the uplift of the earth and the action of the rains and river flows in eroding away the lands. The sum of all the energy involved in this geologic process is useful to man due to the river that is formed. A simplified representation of the geologic energy is shown in Fig. 12a. No calculations were made to determine this large scale geologic contribution to man.

A second (and at a slightly smaller scale) way of calculating the natural energy of the basin is to calculate the various energies involved in the riverine system. This would include the flow of the river, the energy released due to the drop in elevation (river head), and the chemical energy of mixing. The chemical mixing energy of the water is attributable to the relatively low concentration of dissolved substances compared to the ocean (the ultimate sink). In many river systems, the biological productivity is another source of natural energy. In the Mississippi River the autotrophic production is relatively low and the biological food chains are more dependent on heterotrophic systems.

Fig. 12b presents a simplified model of the natural energies associated with the Mississippi River compared to the fuel energies of the barge system using the river. The natural energies contributed are less than the energies of the barge system.

Another possible way of calculating the natural energy of the river system is to consider the energy that man must expend to maintain it in a channelized condition. The rate at which the sediment is replaced in the channel (and therefore the amount of dredging required) may be equivalent to the natural energy of creating and maintaining a river basin. Currently approximately 14.5×10^{12} BTU's of fossil fuel energy are required to harness 16.09×10^{12} BTU's of natural energy.

While all of the natural physical and biological processes constitute a free energy subsidy to man, man can increase the total energy flow by changing the river system. Man's activities based on fossil fuel energies are another energy contribution to the Mississippi region. These energies



ALL FLOWS ARE IN BTU-FFE/YEAR.

$$\text{INVESTMENT RATIO (IR)} = \frac{\text{FF IN MANAGING RIVER}}{\text{NATURAL ENERGIES}} = \frac{14.5}{16.09} = 0.9$$

$$\text{IR} = \frac{\text{FF IN MANAGING RIVER + BARGE AND SHORE FACILITIES}}{\text{NATURAL ENERGIES}} = \frac{192}{16.09} = 11.9$$

(b)

Figure 12. Natural Energies Associated with the Mississippi Watershed.

a. Large scale natural energy subsidies.

b. Natural energies associated with the river system that contribute directly and indirectly to man. Investment ratios are given for the larger system as well as the energy required to harness the river.

Footnotes to Figure 12

1. The energy of the river can be interpreted as an energy subsidy to the Inland Waterway System. An approximate value for the total kinetic energy of the Mississippi River system can be calculated from average measurements at New Orleans. The average discharge at this point is approximately 620,000 cfs (Lauff, 1967) and the mean velocity is about 6 ft/sec (Reid and Wood, 1976). The average total kinetic energy/yr is

$$\text{Kinetic Energy} = \frac{62.4\ \text{lbm/ft}^3}{32.17\ \text{lbm/slug}} \times \frac{0.62 \times 10^6 \text{ft}^3}{\text{sec}} \times \frac{31.536 \times 10^6 \text{sec}}{\text{yr}}$$

$$\times\ 36 \frac{\text{ft}^2}{\text{sec}^2}$$

$$\text{K.E.} = 1365.3 \times 10^{12} \text{ft-lb}$$

$$\text{K.E.} = 1.76 \times 10^{12} \times \frac{1\text{BTU(FFCE)}}{0.62\text{BTU K.E.}} = 2.83 \times 10^{12} \text{BTU CE/region/yr}$$

The energy quality of the kinetic energy of water may be 1.61 more concentrated than fossil fuel (Boynton, 1975). See Table 2. $\frac{1}{0.62} = 1.61$

2. Fresh Water Dilutant:

$$\text{Power } P_{FD} = (\Delta F)(V)(m_s) = (nRT \ln \frac{c_1}{c_2}\ (V)(m_s)$$

n = 1 mole/35 gm; R = gas constant = 1.99 cal/mole K

T = annual mean water temp = ?
assumed to be $15^oC = 288^oK$

c_1 = concentration of dissolved solute in upper Mississippi = 6.3 ppm

c_2 = solute concentration of seawater as sink = 35000 ppm

V = Total freshwater in region =

$$\text{volume} = 40\ \text{in/yr} \times \frac{2.54\ \text{cm}}{\text{in}} \times \frac{1\text{m}}{100\ \text{cm}} \times 1.25 \times 10^6 \text{miles}^2$$

$$\times \frac{2.787 \times 10^7 \text{ft}^2}{\text{mi}^2} \times \frac{0.0929\ \text{m}^2}{1\ \text{ft}^2} = 3.279 \times 10^{12} \text{m}^3\text{/yr}$$

$$\Delta F = \frac{1\text{m}}{35\ \text{gm}} \quad \frac{1.99 \times 10^{-3} \text{kcal}}{\text{m}^o\text{K}} (288^o\text{K}) \times \ln \frac{6.3}{35000}$$

Footnotes to Figure 12 (cont.)

$$P_{FD} = (-0.14119 \frac{\text{kcal}}{\text{gm solute}}) \times (3.279 \times 10^{12} m^3/yr)(6.3\ g/m^3)$$

$P = 11.57 \times 10^{12}$ BTU/region/yr (in CE (or FFCE) and in heat)

3. Primary Productivity of Mississippi and Missouri Rivers

We could not find the area of the Mississippi and Missouri Rivers here so assumed an average width = 0.568 mi

Approximate length of Mississippi and Missouri Rivers (USGS, 1974)=3986 mi

Area = width x length

$A = 2265\ mi^2$

Gross Primary Productivity of the waters assumed to be 4 kcal/m^2/day since we could not locate any data here

Productivity of region (GPP) and Prod/m^2/day x area x days/yr

$$GPP = 4\ kcal/m^2/day \times 2265\ mi^2 \times \frac{640\ acre}{m^2} \times \frac{4047\ m^2}{acre} \times 365\ days/yr$$

$GPP = 8.565 \times 10^{12}$ kcal/rivers/yr (heat equivalents) $\div$ 20 kcal CE/kcal

$GPP = 4.28 \times 10^{11}$ kcal CE/rivers/yr x 3.968 BTU/kcal

$GPP = 1.698 \times 10^{12}$ BTU CE/rivers/yr

An accurate analysis of this would include the primary productivity of the water as well as that of the rivers, swamps, and floodplains. The value presented here is probably incorrect since we did not have the available data and we are attempting only to show the techniques of how to calculate natural productivity on the same basis as fossil fuels.

4. See footnote 6 to Figure 11. Only current Corps of Engineers budget is used (14.5×10^{12} BTU CE/yr) to calculate present situation.

5. See footnotes 4 and 5 to Figure 11. 121.3×10^{12} BTU CE/yr + 56.2 x 10^{12} BTU CE/yr = 177.5×10^{12} BTU CE/yr

can be increased (increased barge traffic) by making changes (harnessing) in the free river energy. While the natural energies may be somwhat reduced, the total energies may be increased. This harnessing of river energies costs fossil fuel energy (and money), and if the total energies were not increased, the Corps of Engineers could not justify making the river changes. The ideal is to maximize both types of energy flow within the basin.

At a regional scale the investment ratio concept (see section II-A) allows a comparison of the natural and fossil fuel energies in the river basin. When the natural energies are high, they are a relatively free subsidy to man, and so a society develops to take advantage of them (the barge system, timber industry, etc.). Different regions will have differing investment ratios, and, as pointed out in section II-A, this ratio may be an indication of economic competitiveness. Determination of this ratio for the Mississippi Basin would allow comparison to other regions and speculation about the possible future growth of the area.

2. Effects of man's activities on the natural energy flows. All the natural processes of the river are affected in varying degrees by man's activities. The impact of Lock and Dam #26 on flora and fauna of the river system is presented in the model in Fig. 13. The river basin with its water, nutrients, plankton, and fish are shown in the main compartment. The adjacent willow floodplain community contributes organic matter to the river system. The major effects of the Corps of Engineers is flooding of the floodplain swamps, resuspension of sediment due to dredging, and creation of channels; all of these activities enable barge traffic to travel the river on a year-round basis. All of these flows can be quantified for the river with and without the proposed Locks and Dam 26. The data for both natural and human storages and flows are probably available in the literature, but the limited scope of the present project did not include these evaluations.

The impact of the Corps of Engineers' activities on the river system can also be considered on a larger scale. This is presented in Fig. 14. The physical energy of the water flow is balanced by the energy of the banks and curves in the river. The meanders and floodplains which were a part of the original river system played a role in the maintenance of that system. Levees have reduced floodplains, reducing flooding during storms and transferred the river energy downstream. River straightening, sand bar elimination, and channel deepening have likewise altered the natural physical processes. When these are altered, the roles of the river system in other activities is also changed. The balance between the sediment load and the river energy is altered by the dams and channels. It is the natural energies at this scale (represented by Fig. 14) which should be quantified before any enlargement of the dams and levees is considered.

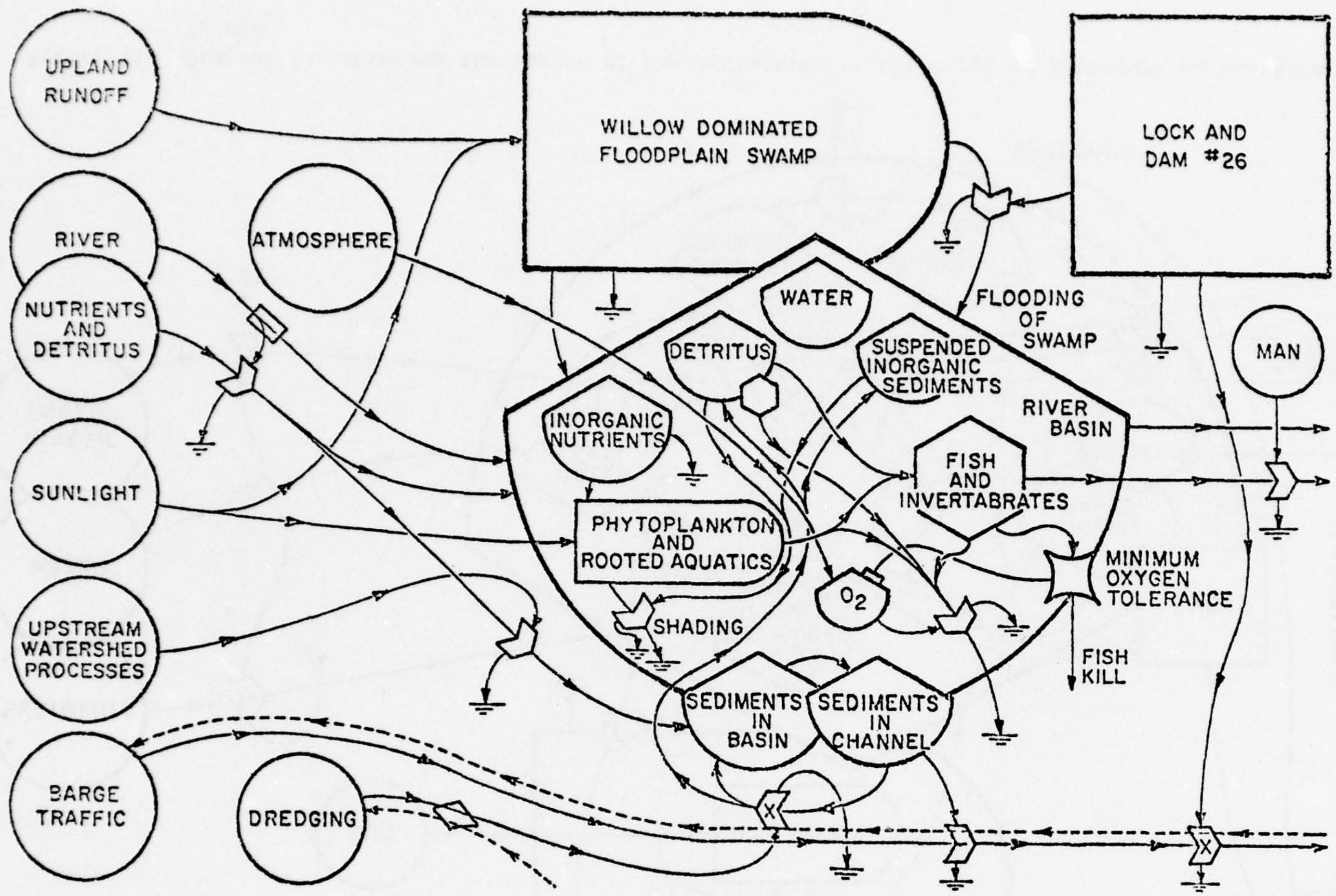


Figure 13. Diagram Illustrating the Impact of Locks and Dam No. 26 on the Flora and Fauna of the River System.

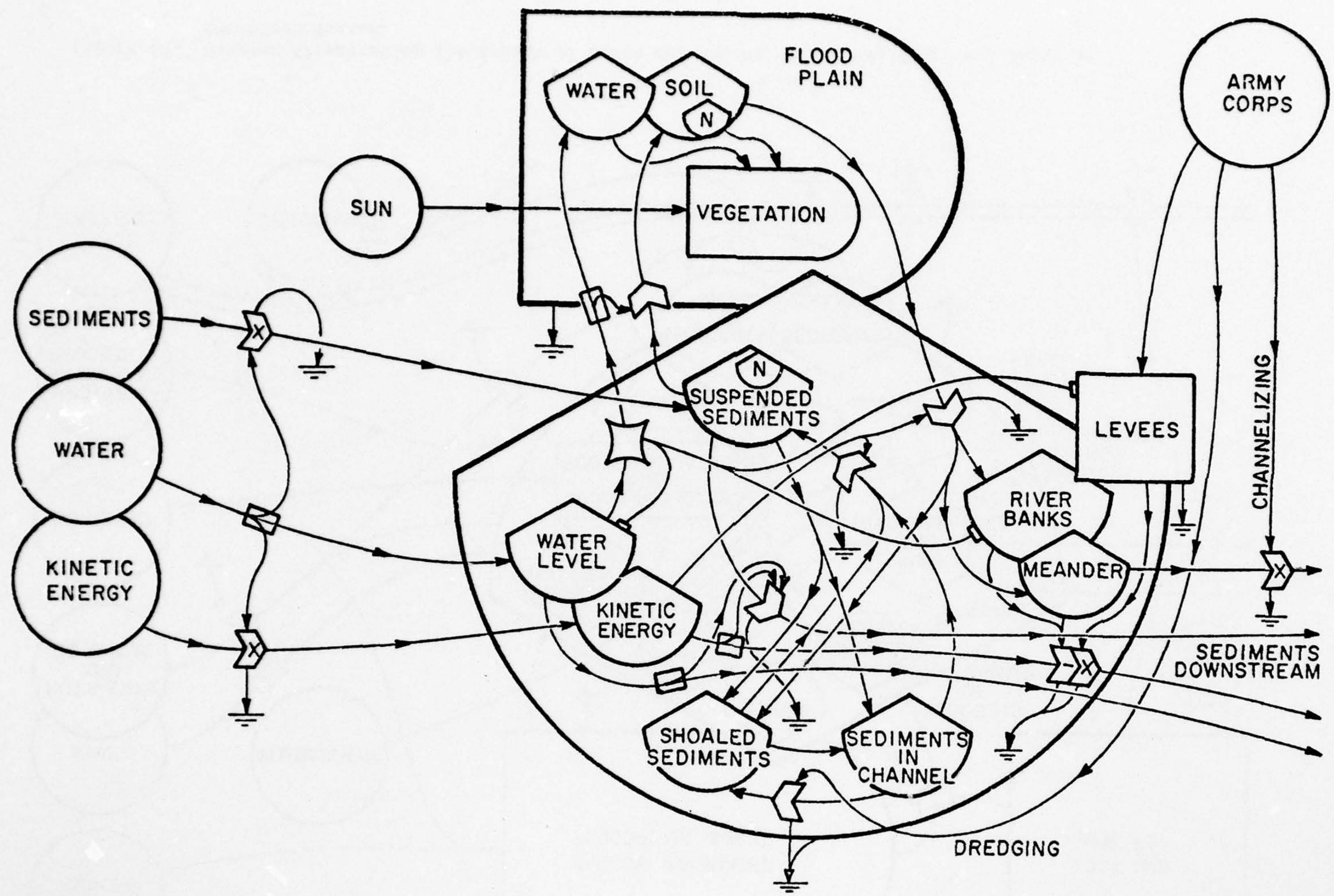


Figure 14. Diagram Illustrating the Impact of the Activities of the Corps of Engineers on the River System.

B. Energetic Analysis of Railroad Transportation

The railroad industry, despite its recent decline in importance, may again figure prominently as America relies more and more on its western coal reserves. Rail transportation is presently "costed," from both inside and outside the industry, in terms of dollars. Shipping rates, like those of other transportation modes, are the products of various forces and as such may not reflect the energy cost of transporting goods. Some studies have considered the energy cost of transport systems. Hannon (1974) discusses the use of input/output theory to obtain BTU/$ ratio for various sectors of the economy. Dollar flows can then be multiplied by the proper ratio and the energy value of certain products can be obtained. In fact, some of these ratios have been used in this report to obtain energy values. They have been augmented, however, to include the work contributed by the natural systems (Section II-A). In another report, Sebald and Herendeen (1974) energetically analyze rail transport. However, they only take into account the direct energy consumed, which is motive fuel, and lighting and heating of offices and terminals. In this report energy usage of rail transport is traced back to primary sources. A detailed analysis in terms of energy would help separate the energy cost of transportation from the effects of labor, profit, or some form of regulation. In the present report, energy analysis is applied to the specific case of a unit train-coal transport system.

In order to compete for the transportation of coal, the unit train concept was developed and put into practice in 1959. The objective of railroad management was to achieve the lowest possible transportation cost. The unit train consists of a dedicated set of haulage equipment loaded at one origin and unloaded at one destination point each trip. Lowest dollar costs are achieved when only one carrier company is involved.

Since unit trains will be involved in the shipment of coal from the Northern Great Plains, data from this geographical area was obtained in order to quantify the systems diagram in Fig. 15. The model is a pictorial representation of those interactions which need be considered in order to determine the energy cost of the unit train transportation of coal. No new rail mileage from the mine site to existing main lines was considered necessary, so this rather large percentage of energy input was not included in the following calculation. It is assumed that no new rail is required for this analysis. A later analysis includes the cost of new rail requirements.

The main components considered were:

1. The energy involved in constructing a new unit train capable of hauling [illegible] tons/yr. (J_1).
2. The energy value of maintenance and operation of the system (J_2).
3. The energy value of diesel fuel usage (J_3).
4. The energy cost of the loading and unloading facilities (J_4 and J_5)

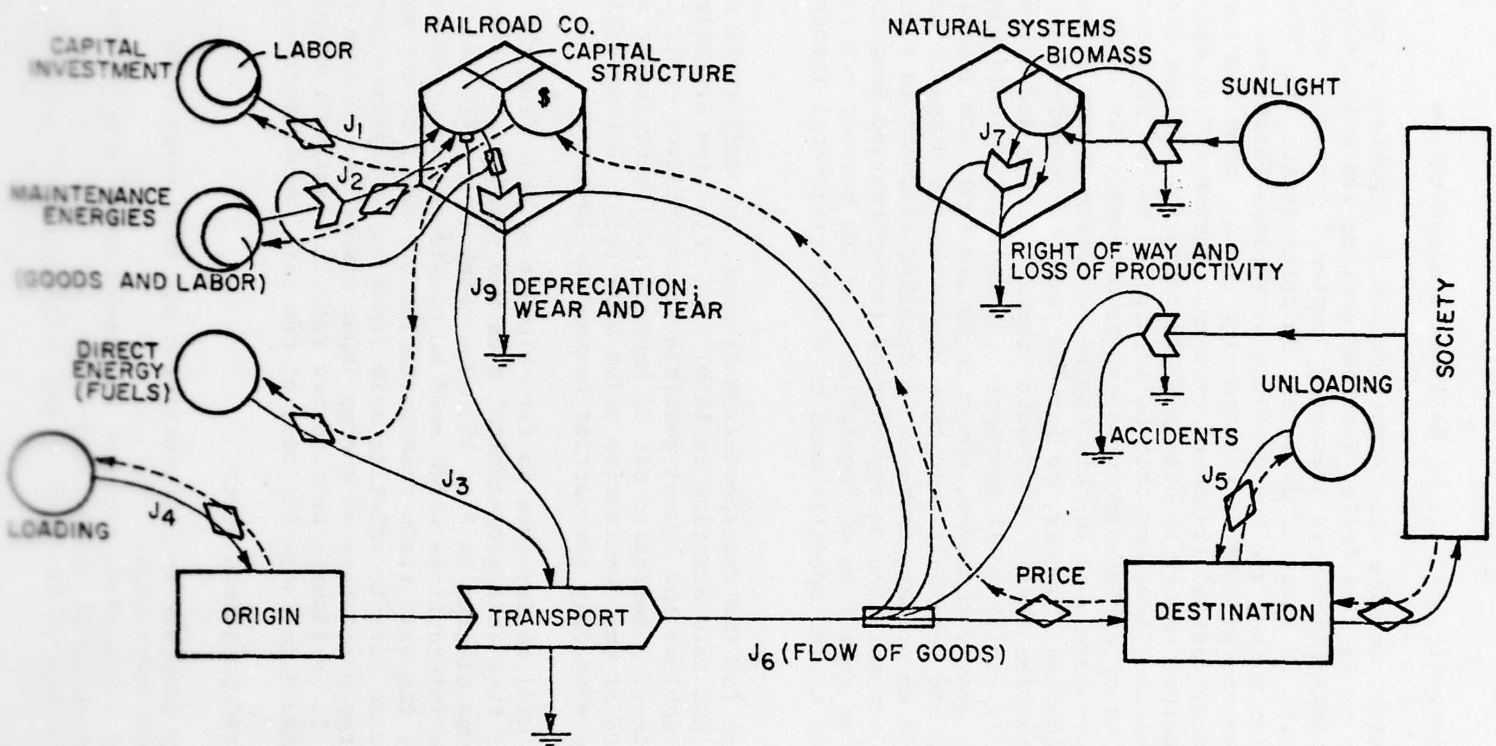


Figure 15. Major Components, Flows, and Interactions Associated with a Unit Train Transporting Goods from One Origin to One Destination.

5. The energy loss due to the destruction of natural ecosystems (J_7).

Table 8 is a breakdown of the energy requirements for the unit train transport of 500,000 tons of coal 800 miles. The specific case using 500,000 tons over a route of approximately 800 miles was chosen since, being an existing route, the data was available to do a meaningful analysis.

Several important energy "costs" had to be eliminated from this analysis due to a lack of data and/or field work. Examples would be the energy losses due to accidents and to the hydrologic perturbations caused by running track through established natural communities. The loss of stored energy value resulting from the destruction of near surface aquifers may be quite large but at present is technically unobtainable. Nevertheless, with the data assembled in Table 8, several interesting aspects of unit train transportation can be explored. One such aspect is a net energy analysis.

In order to calculate the net energy involved in the transport of 500,000 tons of coal 800 miles it is necessary to calculate the energy value of the freight. In the case of coal this is easily done. From Bureau of Mine data, 500,000 tons of NGP sub-bituminous coal would contain approximately 10.0×10^{2} BTU FFE*. This is the gross energy delivered (E_{coal}). The net energy of transportation is $E_{coal} - E_{costs}$. From Table 8 the energy costs can be calculated.

$$E_{costs} = J_1 + J_2 + J_3 + J_4 + J_5 + J_7 = 20.9 \times 10^{10} \text{BTU}$$

The net energy of transport is then

$$E_{coal} - E_{costs} = 10 \times 10^{12} - .21 \times 10^{12} = 9.79 \times 10^{12} \text{BTU}$$

This is represented in Fig. 16. As can be seen, 98% of the delivered energy is net. It should be pointed out again that data are at present not obtainable for many environmental effects which may be important. Data do not exist on the downstream effects of water table drawdown or increased runoff. Much field experimentation and observation must be done before a true energy assessment can be made.

Figure 16 also gives the yield ratio for the distance of 800 miles, an actual coal route. At almost 50:1 the unit train is a very profitable means of transport. It can also be seen that 85% of the cost of transportation is involved in maintenance and diesel fuel usage.

Another interesting comparison would be how both energy and dollar values change with distance. Figure 17 shows both rates and total dollar costs

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* (10,000 BTU/lb x 2000lb/ton x 500,000 tons = 10×10^{12} BTU FFE); Fossil fuel equivalent (FFE) is the same as fossil fuel coal equivalents (FFCE) or coal equivalents (CE).

Table 8

Energy and Dollar Costs Associated with Transporting 500,000 Tons of Coal by Unit Train 800 Rail Miles from Mine Mouth in Colstrip, Wyoming to St. Paul, Minn.

Description	1974 dollar cost per year	Energy cost (10^{10} BTU-FFCE)	Energy cost, BTU per ton-mile[m]
Hopper cars (J_1)	44,625[a]	.8[b]	20.0
Locomotives (J_1)	37,500[c]	.67[d]	16.8
Loading and unloading (J_4 and J_5)	12,500[e]	.22[f]	5.5
Maintenance (J_2)	215,400[g]	1.71[h]	42.8
Diesel Fuel usage by locomotive	271,376[i]	16[j]	400.0
Loss of productivity of natural systems		1.5[k]	37.5
Total energy cost		20.9	522.6

[a] A typical unit train consists of 105 hopper cars at $17,000 apiece (NGPRP 1974 V-3) assuming a 40 year life span for the cars.

$$105 \times 17{,}000/40 \text{ yrs} = \$44{,}625$$

[b] Steel and aluminum IO Sector 1974 BTU/$ ratios are presented in Table 15. To convert the dollar cost of cars and locomotives to BTU-FFCE's an average of these two was used.

$$\frac{\text{steel} + \text{aluminum}}{2} = \frac{114{,}345 \text{ BTU/\$} + 206{,}033 \text{ BTU/\$}}{2}$$

$$= 1.6 \times 10^5 \text{BTU/\$}$$

also assume $\frac{19{,}200 \text{ BTU}}{\$}$ is the natural energy contribution as discussed in Section II-A. $\$44{,}625 \times [\frac{1.6 \times 10^5 \text{BTU}}{\$} + \frac{19{,}200 \text{ BTU}}{\$}] = 7.99 \times 10^9$

Footnotes to Table 8 (cont.)

[c] Assume 5 locomotives at 3,000 hp apiece are needed for a train this size (NGRP, 1974 V-6) at a cost of \$100/engine hp (Ferguson, 1975)

$$\frac{5 \times 3{,}000 \text{ hp} \times \frac{100}{\text{hp}}}{40 \text{ years}} = \$37{,}000/\text{yr}$$

[d] $$\$37{,}500 \times \left[\frac{1.6 \times 10^5 \text{BTU}}{\$} + \frac{19{,}200 \text{ BTU}}{\$}\right] = 6.7 \times 10^9 \text{BTU}$$

[e] Estimates for loading and unloading facilities are \$500,000 (NGRP, 1974 V-6). This is then amortized over 40 years.

$$\$500{,}000/40 = \$12{,}500/\text{yr}$$

[f] $$\$12{,}500 \left[\frac{1.6 \times 10^5 \text{BTU}}{\$} + \frac{19{,}200 \text{ BTU}}{\$}\right] = 2.2 \times 10^9$$

[g] 1. Track maintenance is estimated at $\frac{\$.000146}{\text{ton-mile}}$ (Ferguson, 1975) Thus for an 800 mile route:

$$\frac{\$0.000146}{\text{ton-mile}} \times 800 \text{ miles} \times 500{,}000 \text{ tons} = 58{,}400$$

2. Car maintenance is estimated to be $\frac{\$.000125}{\text{ton-mile}}$ (Ferguson, 1975)

$$\frac{\$0.000125}{\text{ton-mile}} \times 800 \text{ miles} \times 500{,}000 \text{ tons} = \$50{,}000/\text{yr}$$

3. Locomotive maintenance is assumed to be 2.14 times car maintenance (Ferguson, 1975)

$$50{,}000 \times 2.14 = \$107{,}000$$

Total maintenance = 58,400 + 50,000 + 107,000 = \$215,400/yr

[h] The dollar cost of maintenance is converted to BTU by multiplying by the average energy/dollar ratio for 1974 (Ballentine, 1976)

$$\frac{19{,}800 \text{ kcal}}{\$} \times \frac{3.96 \text{ BTU}}{\text{kcal}} = \frac{78{,}408 \text{ BTU}}{\$}$$

$$\$215{,}400 \times [78.408] = 1.69 \times 10^{10} \text{BTU}$$

[i] In 1971 locomotive fuel prices were given as $\frac{\$0.0004846}{\text{ton-mile}}$ (Transportation Statistics). From 1971 to 1974 the price of diesel fuel rose from 10.88¢/gal to 27¢/gal or 40% (Ferguson,1975). The 1974 fuel can then

be calculated as follows:

$$[1.40]\left[\frac{\$0.0004846}{\text{ton-mile}}\right][500{,}000 \text{ tons} \times 800 \text{ miles}] = \$2.7 \times 10^5/\text{year}$$

[j] 33.8×10^8 BTU diesel fuel is used per round trip of a unit train carrying 11,000 tons 1,011 miles from Orin Junction, Wyoming to St. Louis, Mo. (Bureau of Land Management, 1974, Vol. VI, pp. vii-213)

$$\frac{33.8 \times 10^8 \text{ BTU diesel}}{11{,}000 \text{ tons} \times 1{,}011 \text{ miles}} \times \frac{1.32 \text{ BTU FFCE}^*}{\text{BTU diesel}} \times (500{,}000 \times 800 \text{ miles}) =$$

(*quality factor for diesel fuel; Ballentine, 1976) = 1.6×10^{11} BTU FFCE

[k] To calculate the loss of productivity, a right of way of 50 feet x 800 miles is assumed 50 ft = .01 miles

$$.01 \text{ miles} \times 800 \text{ miles} = 8 \text{ miles}^2 \times \frac{2.59 \text{ km}^2}{\text{mile}^2} \times \frac{10^6 \text{m}^2}{\text{km}^2}$$

$$= 20.7 \times 10^6 \text{m}^2 = \text{area of right of way}$$

Assume gross production of grassland Sporobolus community to be $800 \text{ gm/m}^2/\text{yr}$. 1 gm primary production equals 4.5 kcal of sugar equivalent energy. It requires 20 units of sugar equivalent to equal 1 unit of FFCE energy (see Table 2).

$$800 \text{ gm/m}^2/\text{g} \times \frac{4.5 \text{ kcal}}{\text{gm}} \times \frac{1 \text{ FFCE}}{20 \text{ sugar}} \times \frac{3.96 \text{ BTU}}{1 \text{ kcal}} \times 20.7 \times 10^6 \text{m}^2$$

$$= 1.47 \times 10^{10} \text{ BTU FFCE}$$

[m] The numbers in this column were obtained by dividing the total energy cost by 500,000 tons x 800 miles = 4×10^8 ton-miles.

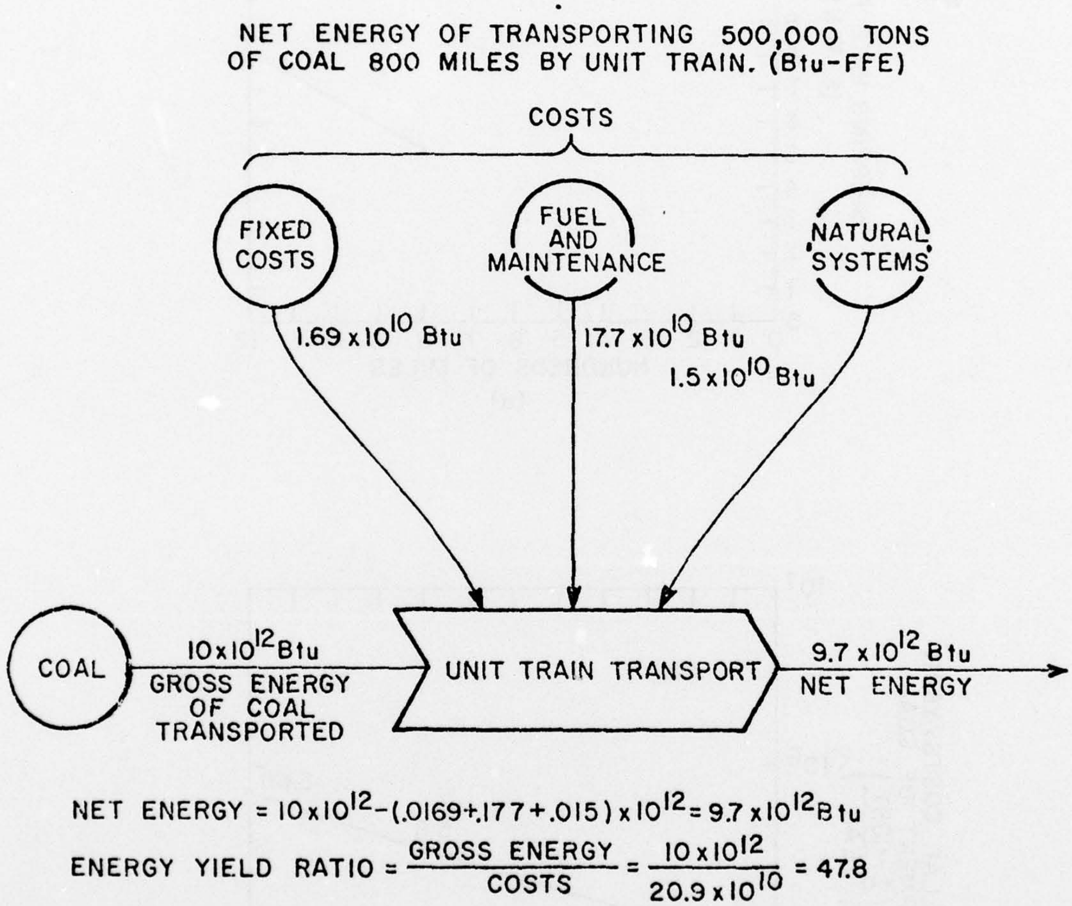

Figure 16. Energy Costs Associated with Transporting 500,000 Tons of Coal a Distance of 800 Miles by Unit Train. All energy units are in BTU coal equivalents. Energy flows are annual rates.

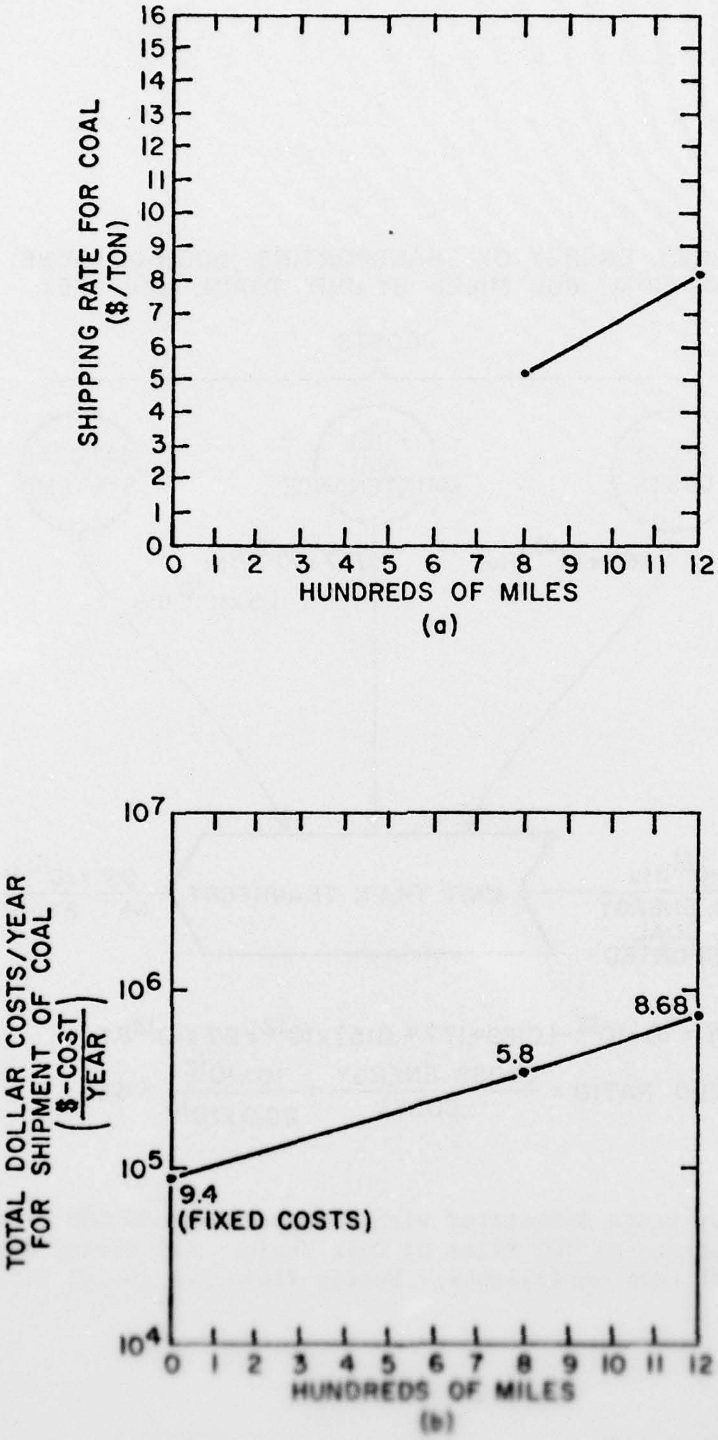

Figure 17. Shipping Rates (a) and Total Dollar Costs (b) for Shipping Coal as a Function of Distance Shipped.

changing with distance. Figure 18 shows the total energy cost increasing with distance. The percent change of these factors is tabulated in Table 9. From this preliminary analysis, it seems that energy costs and dollar cost rise almost identically. This is so even though many of the energy values were calculated uncoupled to the dollar figures; those that were calculated from dollar data utilized different energy/$ ratios. Of course it would be ideal if all energy values were calculated without using dollar conversions. However, at this time the data are not available to do this.

Figure 18 shows the yield ratio decreasing with distance. The yield ratios were calculated by dividing the energy yield by the total cost of transport for various distances. These are tabulated in Table 10. The variable cost of transportation, fuel, maintenance, etc. increases with distance, while the yield, 500,000 tons coal, remains unchanged. Table 11 summarizes the energy costs for various distances. These are plotted in Fig. 18b. The fixed costs of transportation, which is the cost of locomotives hopper cars and loading facilities, does not change. Maintenance and diesel fuel values for various distances were obtained by using the equations which appear in footnotes g, h, i, j and k to Table 8. This graph again supports the fact that coal shipment by unit train is very energy efficient. Even using 3,000 miles as a destination, the transport of 500,000 tons of coal gives a yield ratio of 9.1 units of output for every unit of input energy.

As mentioned earlier, all costs of rail transportation were calculated assuming no new rail mileage would be laid. For comparison a calculation will be made to see the effect of adding in the component cost of new roadbed. Including signaling, communications, terminals, and stations, the cost is estimated to be $\$1.584 \times 10^6$/mile. Amortizing over 100 years = $\$1.58 \times 10^4$/mile/yr and multiplying by 84,088* BTU/$ gives 1.3×10^9 BTU/mile/yr. If this figure is added to the cost of transportation in Fig. 16, the cost goes from 21.7×10^{10} to 1.2×10^{12}. The yield ratio for 1000 miles would be $8.5 \times 10^{12}/1.2 \times 10^{12} = 6.5$.

For purposes of comparison with other sections of this report, net energy and yield ratios have been calculated and normalized to 1000 miles. The mileage used in the previous calculations were actual routes over which coal will travel from the N.G.P. to the midwest. Figure 19 represents the net energy and yield ratios for 1000 miles with and without the creation of new roadbed.

As is shown in Fig. 19b, the energy requirement of new roadbed is considerable, 84% of the total cost of transportation. In fact, 1000 miles of new roadbed is approximately 13% of the coal energy delivered. This brings the

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*new construction IO sector in Table 15.

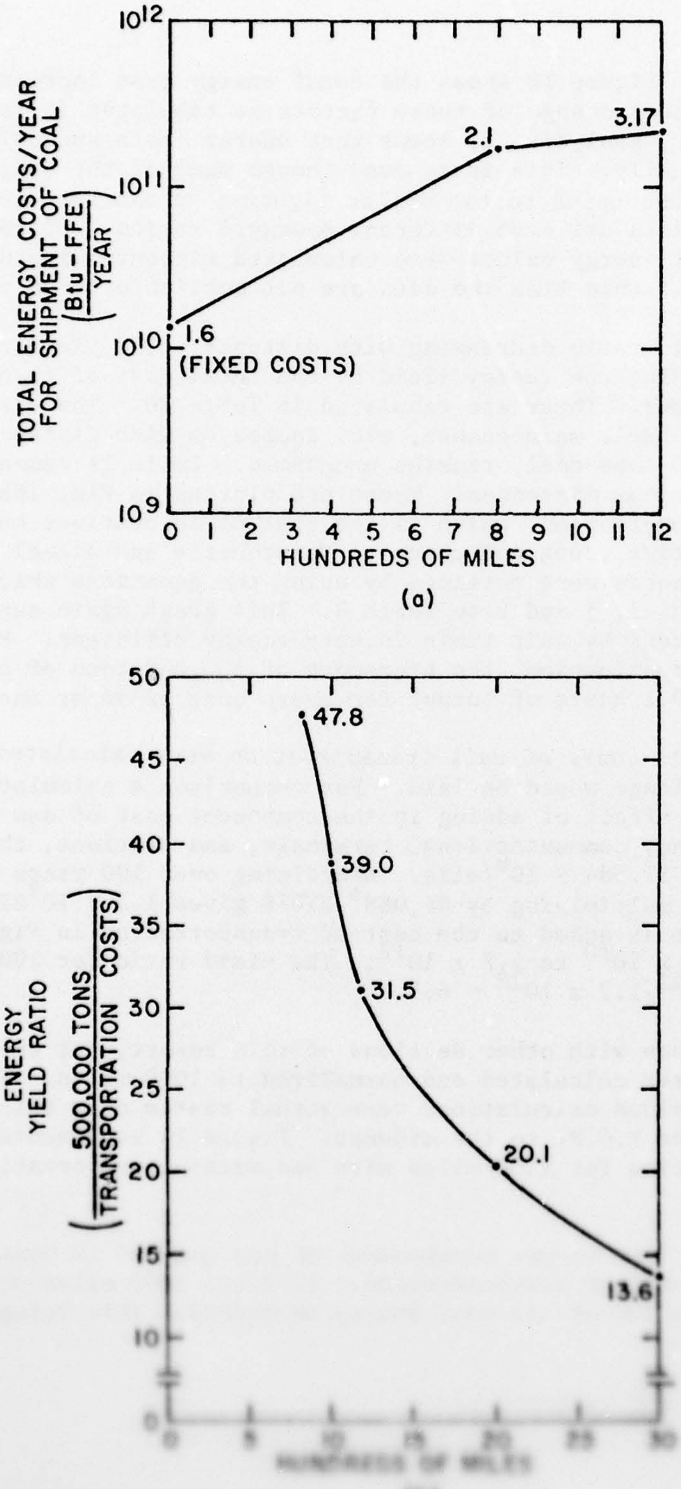
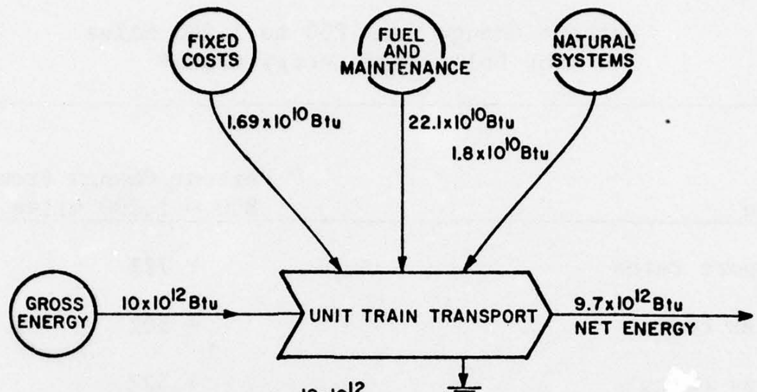


Figure 18. Total Energy Costs (a) and Energy Yield ratio (b) for Shipment of Coal as a Function of Distance.

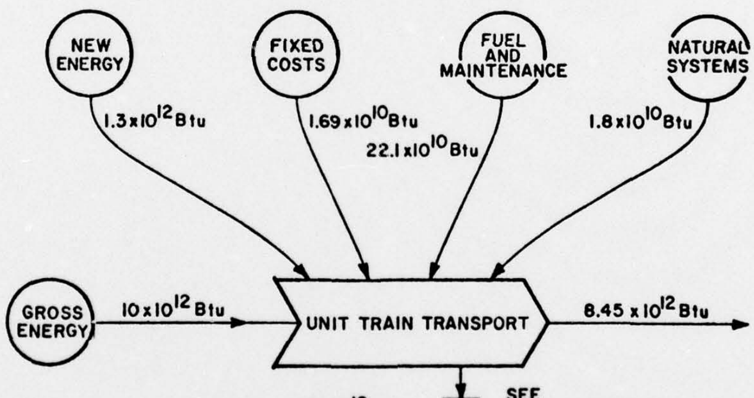
NET ENERGY OF TRANSPORTING [illegible]00,000 TONS
OF COAL 1000 MILES BY UNIT TRAIN. (Btu-FFE)



$$\text{ENERGY YIELD RATIO} = \frac{10\times10^{12}}{25.6\times10^{10}} = 39.0$$

$$\text{NET ENERGY} = 10\times10^{12} - (.0169 + .221 + .018)\times10^{12} = 9.7\times10^{12}\ \text{Btu}$$

(a) NO NEW RAIL BED.



$$\text{ENERGY YIELD RATIO} = \frac{10\times10^{12}}{1.55\times10^{12}} = 645$$

SEE CALCULATIONS INVOLVING NEW ROADBED.

$$\text{NET ENERGY} = 10\times10^{12} - (1.3 + .0169 + .221 + .018)\times10^{12} = 8.45\times10^{12}\ \text{Btu}$$

(b) 1,000 MILE NEW RAIL BED.

Figure 19. a. Energy Costs Associated with Transporting Coal a Distance of 1000 Miles by Unit Train on Existing Track. Energy units in BTU coal equivalents. Energy flows are annual rates.

b. Energy Costs Associated with Transporting Coal a Distance of 1000 Miles by Unit Train on New Track. Energy units in BTU coal equivalents. Energy flows are annual rates.

Table 9

Percent Change from 800 to 1,200 Miles for Dollar and Energy Costs*

Description	Percent Change from 800 - 1,200 miles
Coal transport rates	+ 72%
Total dollar costs	+ 50%
Total energy costs	+ 52%

*See Figs. 17 and 18.

Table 10

The Yield Ratio and Net Energy of Transporting 500,000 Tons of Coal 800, 1000, 1200, 2000 and 3000 Miles by Unit Train

Distance (miles)	Yield Ratio	Net Energy ($x10^{12}$BTU)
800	47.8	9.8
1000	39.0	9.7
1200	31.5	9.68
2000	20.1	9.5
3000	13.6	9.26

Table 11

The Dollar and Energy Costs of Transporting 500,000 Tons of Coal 800, 1000, 1200, and 2000 Miles by Unit Train

	1974 dollar costs/yr				Energy Cost (10^{10}BTU)			
Maintenance	800	1000	1200	200	800	1000	1200	2000
Hopper Cars	44,625	44,625	44,625	44,625	.8	.8	.8	.8
Locomotives	37,500	37,500	37,500	37,500	.67	.67	.67	.67
Loading & unloading	12,500	12,500	12,500	12,500	.22	.22	.22	.22
Maintenance	215,400	269,250	341,947	538,500	1.7	2.1	2.68	4.2
Diesel fuel	271,376	339,220	430,809	678,440	16.0	20.0	25.00	40.0
Loss of primary productivity					1.4	1.8	2.3	3.7
TOTAL COSTS					20.9	25.4	32.7	48.6

yield ratio down from 39 to 6.45. These preliminary calculations indicate that rail transport may be energetically feasible only if existing track is used.

C. Energetic Analysis of Coal Slurry Pipelines

The methodology for evaluating bulk rate transportation systems has been discussed in previous sections. This section will deal specifically with the application of the methodology to coal slurry pipeline systems. The 273 mile long Black Mesa Pipeline, owned by Southern California Edison Co. and operated by the Black Mesa Pipeline Co., is used as the source of both technical information and energy cost estimates. A coal strip mining operation in Kayents, Arizona, supplies coal to the Black Mesa Pipeline Co. for transport to the Mohave Generating Station. The reason for this choice is that the Black Mesa System is the only coal slurry pipeline currently in operation and, in addition, provides the only recent information available on this mode of transport.

An initial explanation of typical system design and operation will provide an overall view of slurry pipeline systems. A schematic energy diagram and discussion will follow in which the individual components and flows will be evaluated. Finally calculations for the Black Mesa Pipeline will be used to estimate energy/ton-mile costs of a comparable pipeline system of 1,000 miles.

Description of a Coal Slurry Pipeline

A typical pipeline system includes a slurry preparation plant, water source, pipeline, pump stations, test loops, control and communication facilities, terminal storage at an electrical generation plant, and dewatering facilities. Coal is received from a coal company at the preparation plant by means of a conveyor belt which delivers particles less than 2 inches into raw coal bins (Montfort). Each bin feeds a process line consisting of an impact crusher, a rod mill, and pumps. The coal is reduced to less than 0.25 inch particles by dry crushing in the impactors and the rod mills pulverize the coal by wet grinding. The coal slurry is formed in the rod mills by the introduction of water. The slurry is then pumped to storage tanks in which the slurry suspension is maintained by means of mechanical agitators Finally, the slurry is pumped to a generating station by means of positive displacement pumps. Pump stations are required along the route (approximately 1 pump station/90 miles) in order to maintain sufficient pressures within the pipeline. A dump pond as well as water pond are provided at each pump station. The former may be utilized to hold coal slurry from the pipeline in case of emergency (i.e., power failure or line break), while the latter may be used for flushing out the pipeline downstream from the pump station (Montfort).

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Upon arrival at the generating station, the coal slurry is stored in tanks with mechanical agitators. From here, the slurry is pumped into large centrifuges where it is dewatered and the coal cake conveyed to pulverizers where it is dried and transported to furnaces for burning. Effluent from the centrifuges is pumped to clariflocculators and is chemically treated to separate the fine particles of coal from the water. From here, the coal "fines" are pumped directly to the furnace and the water is pumped to a circulating water cooling system and finally to an evaporation pond (Dina, 1976). Schematic diagrams fo the entire process are shown in Fig. 20.

Energy Model of Coal Slurry Pipeline

1. Description of flows and storages. The system diagram (Fig. 21) consists of three major compartments (state variables), the coal slurry pipeline system, the U.S. economy, and the natural system. The coal slurry pipeline system is further subdivided into three subsystems: (1) slurry preparation plant, (2) pipeline and pump stations and (3) dewatering facilities. This subdivision facilitates the quantification of dollar costs and energy flows resulting from each part of the slurry process, and it yields comparisons as to the relative energy intensiveness of the various system components. The U.S. economy compartment is also subdivided into the power company and the remainder of the economy. The natural system component is shown as being connected to both the pipeline directly as well as to the slurry preparation plant. The former implies the interaction of energy flows associated with accidents (coal slurry spills) and power failures, while the latter links the water storage of the natural system to the water requirements of the slurry preparation process.

The transported coal is viewed as a flow originating from coal stocks at the slurry preparation plant and sequentially moving through the coal slurry process to the power company and ultimately into the main sector of the U.S. economy. Along the route, the coal can also be viewed as an energy storage, first as coal slurry at the preparation plant, followed by coal slurry in the pipeline, and finally as dewatered coal at the generating station. The flow of coal slurry through the system is thus shown to be energetically coupled to each process of the coal slurry system by the energy inputs required by each to transport the coal along its route.

The energy flows required to construct, operate, and maintain the system are viewed as the purchased energies from the main economy, which are inputs into the slurry preparation compartments, and the natural energy inputs, which drive the natural system as well as providing energy subsidies to the slurry system in the form of water, and in some cases gravity (route dependent). Money is shown to flow counter current to all energy flows purchased by the slurry company.

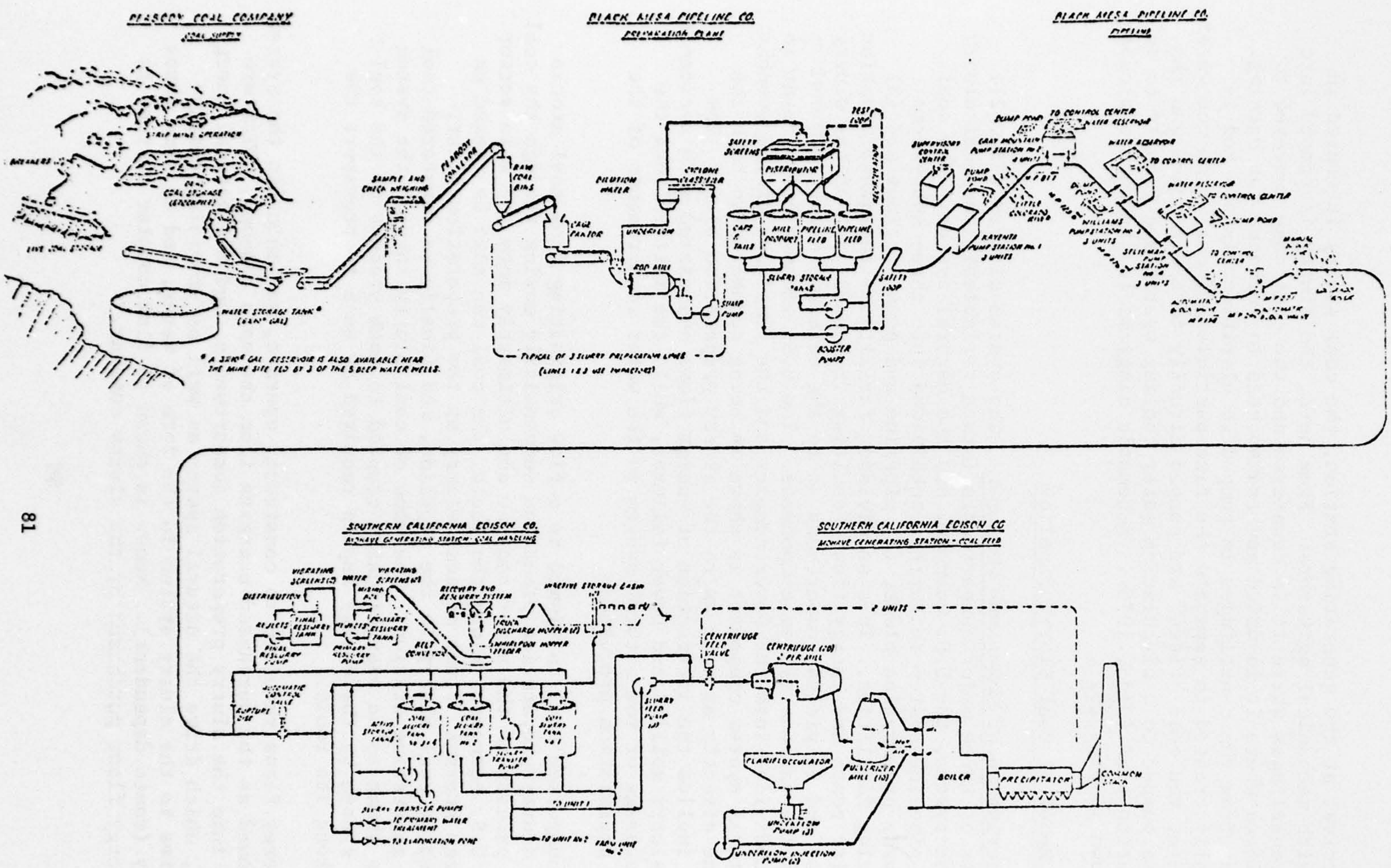

Figure 20. Schematic Diagram of a Coal Slurry Pipeline System. (Taken from Dina, 1976)

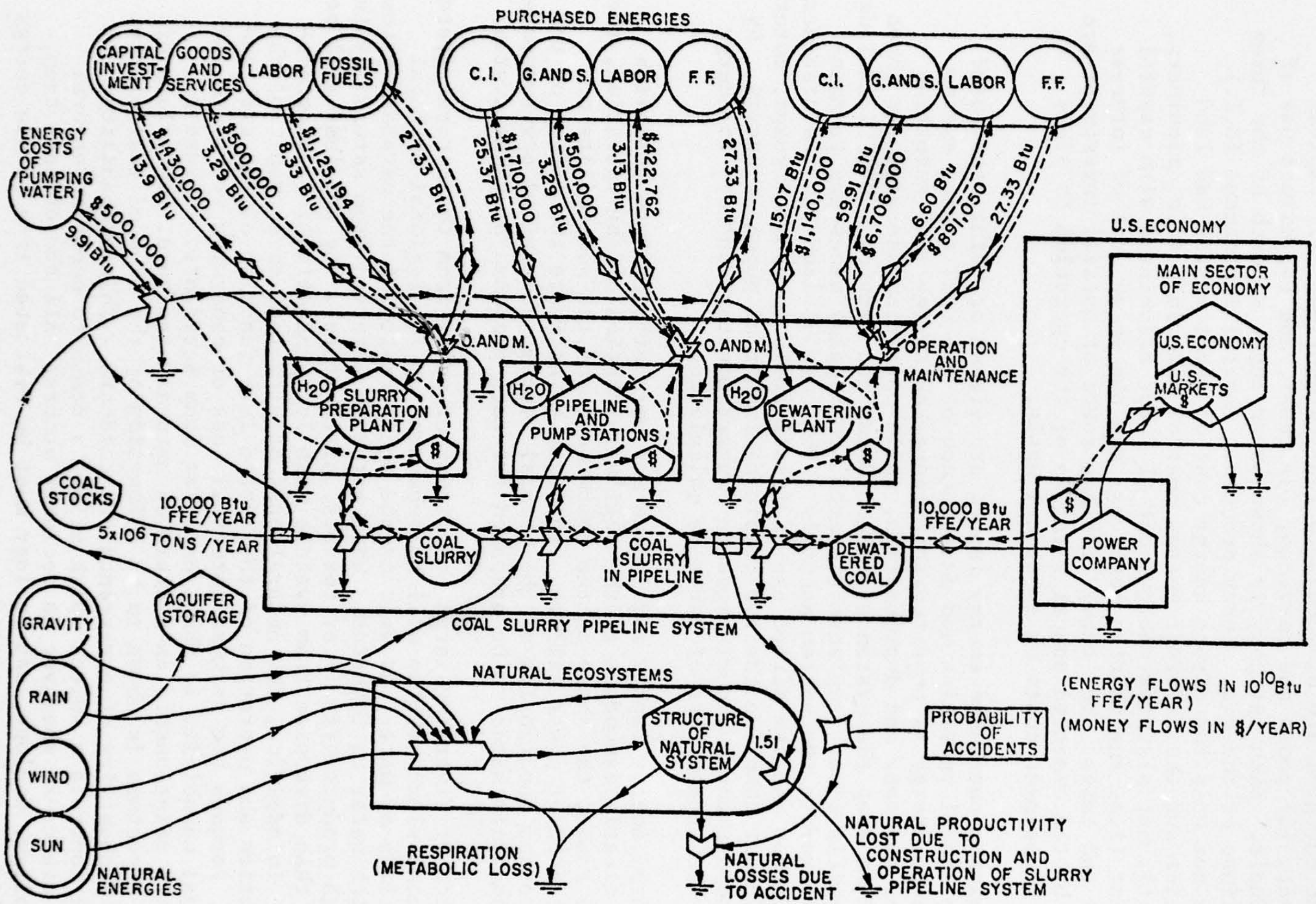

Figure 21. Major Components and Associated Energy and Dollar Flows for a 273 Mile Coal Slurry Pipeline System. Data taken from Black Mesa Pipeline.

Purchased energies are divided into four categories: (1) capital investment, (2) goods and services, (3) labor, and (4) direct use of fossil fuels. Each category is shown as an input to each of the three subdivisions of the coal slurry process. Capital investment (C.I.) includes not only the direct energy cost of construction and land preparation and the indirect energy cost of materials (i.e. machinery, equipment), but also the energy cost of labor associated with capital investment (i.e. engineering services) and the enrgy cost of interest on loans and taxes. The total lifetime costs of capital investment are divided by the expected annual lifetime of the operation to yield capital investment costs on an annual basis.

The remaining purchased energy inputs are viewed as being associated with the annual operation and maintenance of the coal slurry system. Maintenance energy is required to balance the energy loss resulting from wear and tear and depreciation, while operating energies are those required to keep the system running. Goods and services (G + S) include all materials (i.e., replacement parts, chemicals) necessary to maintain and operate the system annually. The cost of labor for maintenance and operation and the direct use of fossil fuels to operate pumps, motors, and equipment comprise the two remaining inputs of purchase energy. By using the estimated annual wages to convert monetary outlays to energy values, the energy cost of labor is calculated.

The natural energy inputs and losses are more difficult to establish and are clearly dependent on the regional location of the operation, the specific route, the scale of the operation, and the possibility of accidents and/or power failure. In order to estimate the effect on the structure and functioning of the natural system, a detailed environmental impact analysis needs to be prepared for each proposed piepline system.

The effect of diverting large quantities of water from the natural system to the coal slurry system will be dependent on the regional or local availability of water, as well as the productivity of the natural systems from which water is diverted. When water is diverted from natural systems with high productivity (i.e. forests, agriculture), the net loss will be greater than diversion from systems with low productivity (i.e. grasslands). In addition, the natural productivity lost as a result of the construction and operation of the system is a function of its size and length. Perhaps the largest potential loss of ecosystem structure and functional capability is that resulting from accidents. Figure 21 shows this relationship as a drain on natural structure. This loss of natural structure is shown to be a function of the flow of coal slurry and the probability of occurrence of accidents. This probability function controls a switch which allows a drain to occur on natural systems sturcture whenever an accident occurs. All the effects then, of hydrology, ecology, and geology must be evaluated if a viable energy evaluation is to be completed.

Gravity is viewed as a "free" natural energy subsidy to the system which is capable of moving the coal slurry within the pipeline. The net value of gravity can be calculated using the route relief profile of the system under consideration.

Quantitative analysis. It should be made clear from the outset that the economic data used to make the detailed energy calculations for coal slurry pipelines was derived from very broad numbers rather than from detailed cost estimates. For example, all energy calculations associated with capital investments were estimated using only total capital investment data for slurry preparation and wells - \$50 x 10^5, pipeline and pump stations - \$60 x 10^6, and dewatering - \$40 x 10^6. Due to the difficulty of obtaining a detailed cost breakdown from the Black Mesa Pipeline Co., a set of assumptions was made concerning the proportion of total costs that was produced by each input-output sector of the economy (see Appendix IV). These assumptions were based on available technical information which describes the type of equipment, machinery, construction, and other inputs necessary for the coal slurry system. All energy calculations should therefore be viewed as gross estimates with the major emphasis placed on the methods rather than the calculated values. Table 12 summarizes energy costs for a 273 mile pipeline.

Analysis of the annual energy inputs required to transport 5 x 10^6 tons/yr of coal slurry over 273 miles shows that the most energy intensive aspect of the operation is the direct use of fossil fuels which requires a total of 82 x 10^{10}BTU/yr or 36% of the total 230 x 10^{10}BTU/yr. Calculations of direct fossil fuel use were made using the figure of 260 BTU/ton/mile (excluding dewatering)(Montfort). Since both coal and electricity were used as fuels, it is important to determine the percentage of each required. This is because electricity is a more concentrated type of fuel with a higher energy quality factor (3.7 $\frac{\text{BTU coal}}{\text{BTU elec}}$). Since there were no available estimates of direct energy use at the dewatering facilities, it was assumed that this process had the same requirements as the slurry preparation plant and the pipeline pump stations (see Appendix IV).

Annual energy inputs associated with goods and services (G + S) constitute the next most energy intensive aspect of the operation, with a total of 66.49 x 10^{10}BTU or 29% of the total. It is important to note that a large percentage of this input (91%) is required at the dewatering facilities for the maintenance of centrifuges and the cost of chemicals for the clariflocculators. Goods and services for the preparation plant and the pipeline and pump stations are small in comparison (3.29 x 10^{10} BTU's for each).

Table 12

Total and Annual Costs of a 273 Mile Coal Slurry Pipeline System (1974 $) [a]

	Total dollars	$/yr	Total energy 10^{10}BTU	10^{10}BTU/yr
CAPITAL INVESTMENT				
Slurry Preparation + Wells	5×10^6	1,430,000	481.60	13.90[b]
Pipeline, Pump Stations	6×10^6	1,710,000	887.80	25.37[c]
Dewatering Facilities	4×10^6	1,140,000	530.25	15.07[d]
Total				54.34
GOODS AND SERVICES				
Slurry Preparant Plant		500,000		3.29[e]
Pipeline, Pump Stations		500,000		3.29[f]
Dewatering Facilities		6,706,000		59.91[g]
Total				66.49
LABOR				
Slurry Preparation Plant		1,125,194		8.33[h]
Pipeline and Pump Stations		422,762		3.13[i]
Dewatering Facilities		891,050		6.60[j]
Total				18.06
DIRECT FOSSIL FUEL USE				
Slurry Preparation Plant				27.33[k]
Pipeline and Pump Stations				27.33[l]

Table 12 (cont.)

	Total dollars	\$/yr	Total energy 10^{10}BTU	10^{10}BTU/yr
DIRECT FOSSIL FUEL USE (cont.)				
Dewatering Facilities				27.33[m]
Total				81.99
WATER (Transport from Wells to Preparation Plant)		500,000		9.91[n]
GRAND TOTAL				230.79

[a]See Appendix IV for footnotes [b-n] detailing calculations.

Energy inputs for capital investments were calculated to be almost as high as those for goods and services, with 54.34×10^{10}BTU/yr or 24% of the total. Although capital investments constitute the highest total energy input to the system, their value is substantially reduced when calculated on an annual basis with an estimated 35 year lifetime (see Appendix IV). A breakdown of capital investment energy inputs reveals that the pipeline and pump stations are the most energy intensive aspects of the process, with 46% of the total energy input versus 25% for the slurry preparation plant and 27% for the dewatering facilities. These relative energy inputs, though, are not reflected by dollar costs since the energy coefficients ($E_j{}^T$BTU/$), for the pipeline steel are approximately four times higher than most other economic input-output sectors.

Labor energies are the lowest of the four inputs of purchased energy, comprising 18.06×10^{10}BTU/yr or 8% of the total energy input. The energy requirements for labor include not only the direct labor costs of 82 employees, but also the administrative costs of labor at the main branch office located at a distance from the coal slurry process. Direct labor costs and associated energy costs comprise 2/3 of the total labor input, while administrative energy accounts for the remaining 1/3 (see Appendix IV).

The annual cost of transporting water from wells to the slurry preparation plant has been calculated separately since this flow is viewed as being coupled to the natural system. The energy input for this transport has been calculated as 9.91×10^{10}BTU/yr or 4% of the total energy input. This represents the cost of 3,000 acre-ft/yr of water at a dollar cost of 0.5×10^6\$/yr (Rieber and Soo, 1975).

The final energy inputs to the coal slurry system are those from the natural system. The use of gravity as an energy subsidy in moving coal from the preparation plant to the generating plant is considered a net energy gain, while losses of natural energy resulting from operation and potential accidents (pipe breakage and subsequent coal slurry "spills") are net losses. Since the utilization of gravity is route dependent, no estimate of its net effect is presented. The loss of natural productivity on site due to coal slurry facilities as well as the productivity lost due to the removal of 3,000 acre-ft/yr from the natural system are presented in Table 13. It can be seen that this net loss (1.51×10^{10} BTU's/FFE/yr) is small relative to the purchased energy requirements of the system (230.79×10^{10}BTU's/yr). The design of the Black Mesa pipeline specifies the dumping of coal slurry in case of power failure. The problem for a 273 mile line with three pumping stations and a 46,000 ton coal hold up is minor compared to a 1000 mile line with 10-12 pump stations and a hold up of 900,000 tons. The case of line break can be similarly handled at upstream points by the introduction of water into the pipe. However, there is no provision made such that the downstream

Table 13

Estimated Annual Loss of Natural Energies Resulting from the Construction and Operation of a 273 Mile Coal Slurry Pipeline

Energy Loss	10^{10} BTU FFE
Productivity lost on site of slurry prep. plant and dewatering facilities	0.01[a]
Productivity lost along route of pipeline	0.63[b]
Productivity lost due to use of water in slurry prep. process	0.87[c]
TOTAL	1.51

[a]It is assumed that the preparation plant and dewatering facilities occupy 40 acres. The gross production of the natural system is assumed to be 800 gm/m^2/yr (Ballentine, 1976) or that of a short grass prairie = (40 acres) x $\frac{4057\ m^2}{acre}$ x (800 gm/m^2.yr) x (4.5 $\frac{kcal}{gm}$) x (3.96 $\frac{BTU}{kcal}$) x $\frac{1\ BTU}{20\ sugar}$ = 0.01 x 10^{10} BTU/yr.

[b]It is assumed that productivity is lost along the 20 meter wide access road along the pipeline route

(273 miles) x (1,607 $\frac{meters}{miles}$) x (20 meters) x (800 gm/m^2/yr) x (4.5 $\frac{kcal}{gm}$) x (3.96 $\frac{BTU}{kcal}$) x $\frac{1\ BTU}{20\ sugar}$ = 0.63 x 10^{10} BTU/yr.

[c]The coal slurry process diverts 3,000 acre-ft/yr of water from the natural system to its use. 1 acre of gross production is assumed lost for each acre-ft of water used in the plant (Ballentine, 1976). Research is needed on this relationship.

(3000 acre x 4057 m^2/acre) x (800 gm/m^2/yr) x 4.5 $\frac{kcal}{gm}$) x (3.96 BTU/kcal) x ($\frac{1\ BTU}{20\ sugar}$) = 0.87 BTU/yr.

pump can pull the slurry through the downstream sections of the break. Hence, the design excludes line breaks, a fact which might result in large losses of natural energy (ecosystem disruption). Baccheti (1971) has indicated that no power failures or line breaks have occurred to date in the Black Mesa Pipeline. Since there are currently no estimates of either the probability of line breaks or power failures and no estimates of the effects on natural systems resulting from such events, these flows are not evaluated in this report.

A summary of the major flows associated with a 273 mile coal slurry pipeline system transporting 5 x 10^6 tons/yr is shown in Fig. 22. Table 14 summarizes the total energy costs/ton-mile, the net energy/ton-mile, direct energy cost, indirect energy cost, and the energy yield ratio. The calculations for the 1000 mile pipeline were made by extrapolation of the costs for the 273 mile pipeline system. Since both systems transport the same amount of coal per year, the costs of slurry preparation facilities and dewatering are viewed as fixed costs, while costs associated with additional pipeline and pump stations will vary as a function of the total distance of the pipeline system.

The total energy cost/ton-mile drops substantially from 1702 BTU/ton-mile for the 273 mile system to 775 BTU/ton-mile for a comparable 1000 mile pipeline. The reason for the decrease is due to the relatively high initial energy costs of the slurry preparation plant and dewatering facilities which are a necessary component of the pipeline system and are independent of the pipeline distance. As the distance of the pipeline route increases, though, only the additional costs associated with the extra pipeline and pump stations are incurred making the total energy cost/ton-mile decrease as the total distance increases.

Net energy/ton-mile is also shown to decrease significantly from 71,575 BTU/ton-mile for the 273 mile pipeline to 19,228 BTU/ton-mile for a comparable 1000 mile system. An examination of the net energy for each system reveals that both systems deliver roughly the same amount, 9.77 x 10^{13} BTU/yr for the 273 mile system versus 9.61 x 10^{13} BTU/yr. This similarity is due to the fact that total energy value of the delivered coal, which is the same for both systems, far exceeds the additional energy costs of increasing the pipeline distance and therefore does not greatly affect the net energy cost calculations. The reason then for the decrease in the net energy/ton-mile between the two systems can be accounted for by the increased distance of the pipeline system.

The yield ratio is equal to the ratio of the energy transported divided by the total energy cost of the system. Since the energy value of the transported coal is constant for both systems but the total energy cost increases as the pipeline distance increases, it is clear that the yield ratio will decrease as the pipeline distance increases. A graph

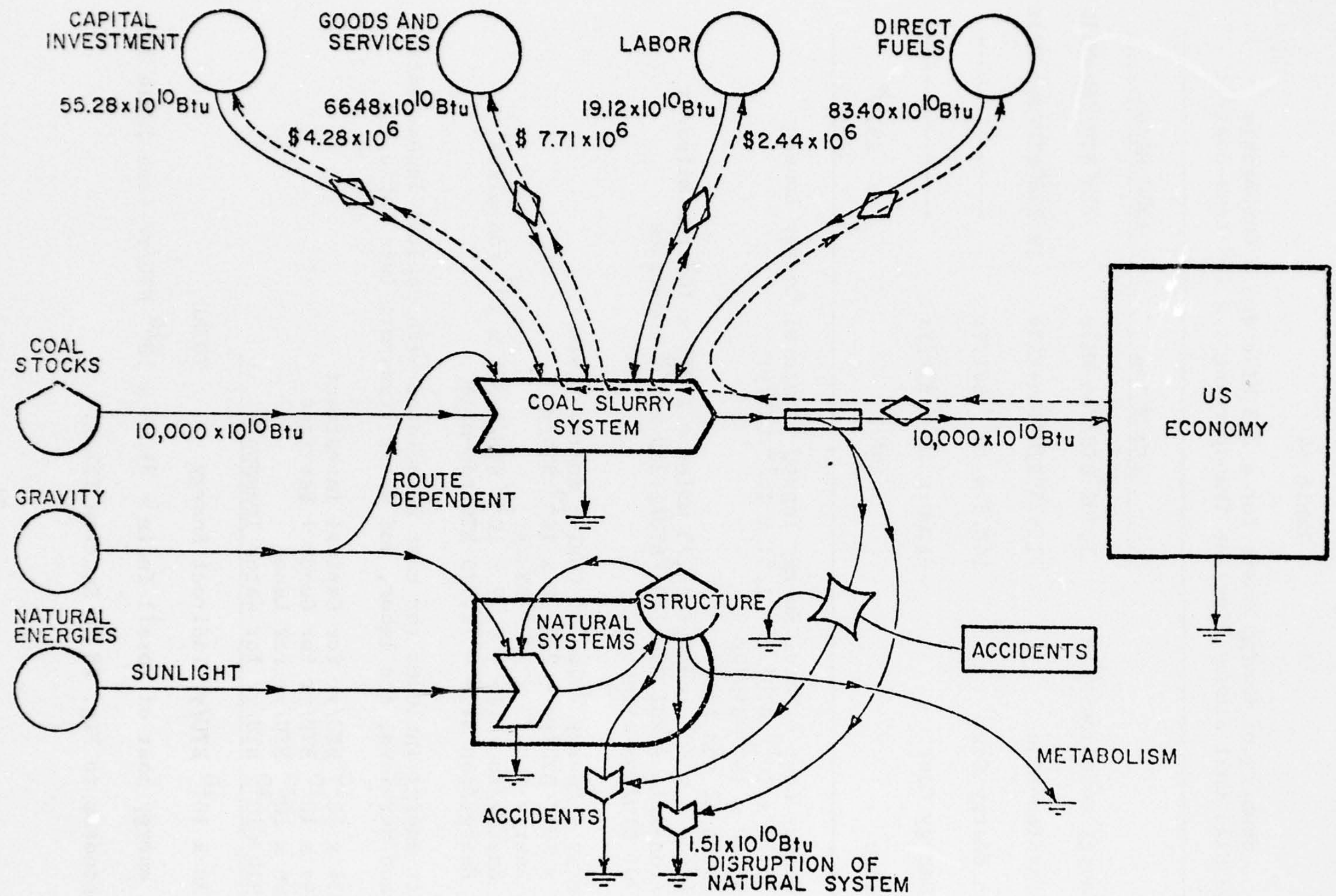

Figure 22. Simplified Diagram of a 273 Mile Coal Slurry Pipeline System with Major Energy and Dollar Flows for Transporting 5 x 10^6 Tons/Yr.

Table 14

Summary of Energy Costs for a 273 Mile and a Comparable 1000 Mile Coal Slurry Pipeline Transporting 5×10^6 tons coal/yr

	273 Miles	1000 Miles
Total Energy Cost/Ton-Mile	1,702[a] BTU/Ton-Mile	775[f] BTU/Ton-Mile
Net Energy/Ton-Mile	71,575[b] BTU/Ton-Mile	19,228[g] BTU/Ton-Mile
Indirect Energy Cost	148.8×10^{10} [c] BTU/Yr	--------------
Direct Energy Cost	81.00×10^{10} [d] BTU/Yr	--------------
Yield Ratio	43[e]	25.8[h]

[a]Total Energy Cost = Total Energy Inputs + Natural Energy Losses
$= 230.79 \times 10^{10}$ BTU/yr + 1.51×10^{10} BTU/yr
$= 232.30 \times 10^{10}$ BTU/yr
(see Tables 12 and 13).
ton-miles = 5×10^6 tons/yr x 273 miles = 1.365×10^9 ton-miles/yr
Energy/ton-mile - 232.30×10^{10} BTU/1.365×10^9 ton-miles
= 1702 BTU/ton-mile

[b]Net Energy - Energy Value of Coal - Energy Costs
$= 1 \times 10^{14}$ BTU/yr - 232.30×10^{10} BTU/yr
Net Energy = 9.77×10^{13} BTU/yr
Net Energy/ton-mile = 9.77×10^{13} BTU/1.365×10^9 ton-miles
Net Energy/ton-mile = 71,575 BTU/ton-mile

[c]Indirect energy includes the cost associated with capital investments, goods and services, and labor, and water transport (see Table 12).

54.34×10^{10} BTU/yr for Capital Investment
66.49×10^{10} BTU/yr for Goods + Services
18.06×10^{10} BTU/yr for Labor
9.910×10^{10} BTU/yr for Water Transport

148.80×10^{10} BTU/yr Indirect Energy TOTAL

[d]Direct energy cost of fossil fuels = 81.99×10^{10} BTU/yr (see Table 12).

[e]See footnotes to Fig. 28 in Section III-E.

Footnotes to Table 14 (cont.)

[f] Total energy cost for 1000 mile pipeline = 387.55×10^{10} BTU/yr (see footnote 4 to Fig. 28).

Ton-miles = 5×10^{6} tons/yr x 1000 miles = 0.5×10^{10} ton-miles/yr

$$\text{Energy/ton-mile} = \frac{387.55 \times 10^{10}\ \text{BTU/yr}}{0.5 \times 10^{10}\ \text{ton-miles/yr}} = 775.10\ \text{BTU/ton-mile}$$

[g] Net Energy = Energy of Coal - Energy Costs
= 1×10^{14} BTU/yr - 387.55×10^{10} BTU/yr
= 9.61×10^{13} BTU/yr

$$\text{Net Energy/ton-mile} = \frac{9.61 \times 10^{13}\ \text{BTU/yr}}{0.5 \times 10^{10}\ \text{ton-miles/yr}} = 19{,}220$$

[h] See footnote 4 to Fig. 28.

of the yield ratio as a function of pipeline distance from 200-2000 miles is shown in Fig. 28.

D. Energetic Analysis of Transmission Lines

There are various ways in which coal from the Northern Great Plains can be transported to cities further east. This transport can involve either direct transport of the coal itself or indirect transport of the coal as another energy form. Direct transport involves transportation by rail, barge, or slurry pipeline. These three methods have been discussed previously. Indirect transport involves the production of electricity from the coal at the mine mouth, and the distribution of this electrical power by way of transmission lines. This section discusses this latter method. However, only the long distance transmission of electrical power will be considered since the production of electrical power is common to all the alternatives.

For the purposes of this section, three assumptions were made and various parameters were drawn up on the basis of these assumptions. First, it was assumed that the line itself would originate at the mine mouth and extend over a distance of approximately 1000 miles. Due to such a long distance, a high voltage transmission line is necessary. Also, such a line is capable of supplying the amount of electrical power demanded by a large metropolitan area. The line losses of a lower voltage line are so great that use of such a line over this distance is totally impractical, not only in terms of line losses, but also in terms of the cost per unit of energy transferred (Waddicor, 1964).

The length of the line also has an influence on the way in which the power can be transmitted. Due to such a long line distance, the use of a DC power transmission line, as well as an AC transmission line, is feasible. This is possible because the break-even distance above which DC transmission is economically feasible as compared with AC transmission is 400 to 600 miles (BPA, 1970). Therefore, there are several options for transmitting electrical energy from a region such as the Great Plains. The most likely transmission systems are: one, a 765-KV AC line; two, a ±400-KV DC line; and three, a ±600-KV DC line.

The second assumption was that the terrain over which the line would pass would consist of gently rolling hills and flat prairie. Such a relatively flat terrain would allow for wide spacing of the supporting structures of the line. These long spans, along with the high voltage of the line, dictate the use of steel lattice towers for each of the three voltage options previously stated (Taylor, 1927). The assumption of a relatively flat terrain has a definite effect on the cost of the transmission line. A line over a terrain which is more rugged will

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require more and sturdier towers, which would increase the initial cost of the line.

The final assumption was that this power line would not interfere with any existing power or telephone lines. This assumption, along with that of terrain, would allow for uniform spacing between the supporting towers.

Shown in Fig. 23 is a systems model illustrating the major components and inputs necessary for a general transmission line. The solid lines represent the flow of energy, and the broken lines represent the flow of money. Each piece of capital structure has associated with it an energy flow representing capital investment (J_1, J_5, J_{13}, J_{10}, J_{19}). These flows represent the energy expended somewhere else in the economy to construct that capital structure. Likewise, there is an energy cost associated with operation and maintenance for each of the capital structures which includes replacement and labor costs (J_4, J_{14}, J_8, J_{11}, J_{20}). This input of operation and maintenance energy is necessary to offset the energy losses due to depreciation (J_2, J_6, J_9, J_{15}, J_{21}), ane wear and tear (J_3, J_7, J_{12}, J_{16}, J_{22}) of the capital structure. There are also direct energy losses due to transmission and conversion which are represented by J_{17}, J_{18}, and J_{23}. In the event a DC transmission line is used, the AC power generated at the mine mouth must be converted to DC power and the DC power re-converted back to AC power at the termination point. Therefore, converter stations and their losses only apply in the case of transmitting DC power. Also included in the model is the loss of natural energy associated with ecosystem destruction, J_{24}.

Figure 24 shows a detailed model of the effects of a power line on the ecosystems over which it traverses. In this model, J_{24} has been broken down into losses due to the use of herbicides and pesticides, and losses due to clearcutting for the power line right-of-way and access roads to the power line itself. Because this power line extends over several types of ecosystems, the figure does not represent the transmission line's effect on one particular ecosystem, but its overall effect along its 1000 mile route. For instance, clearcutting is not necessary in the Great Plains, but it becomes necessary in forested regions farther east; therefore, it is included in the diagram. As can be seen from the diagram, clearcutting for the transmission line right-of-way and access roads to the power line increases the amount of dead material (litter) as does the use of herbicides and pesticides. Such destruction of the ecosystems increases the runoff from these areas. This runoff transports minerals and humus into local water bodies where it can cause such adverse effects as algal blooms, increased sedimentation rates, etc. (Likens and Bormann, 1970). This ecosystem destruction, as explained in previous sections, can be measured by determining the primary productivity which is lost.

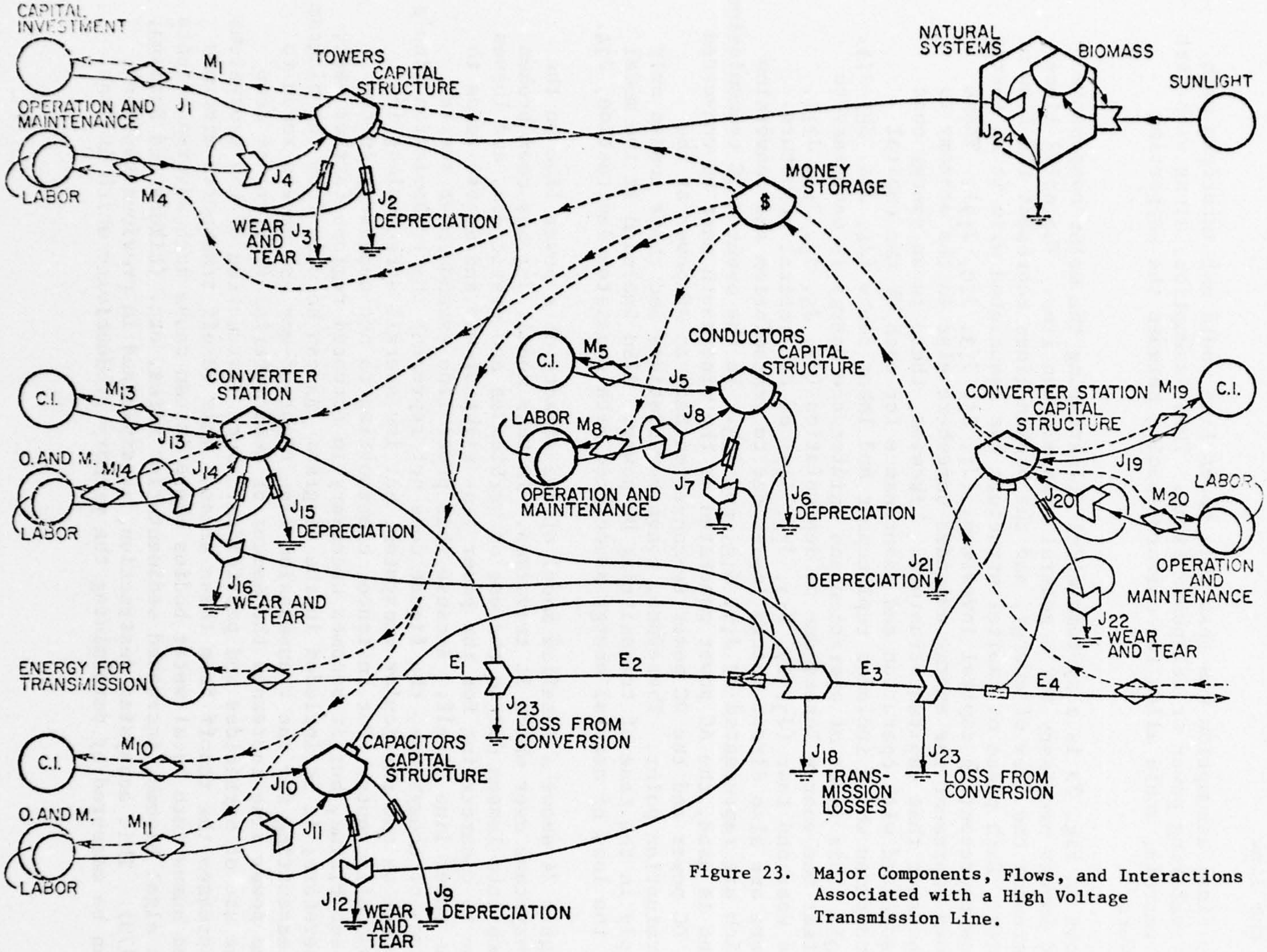

Figure 23. Major Components, Flows, and Interactions Associated with a High Voltage Transmission Line.

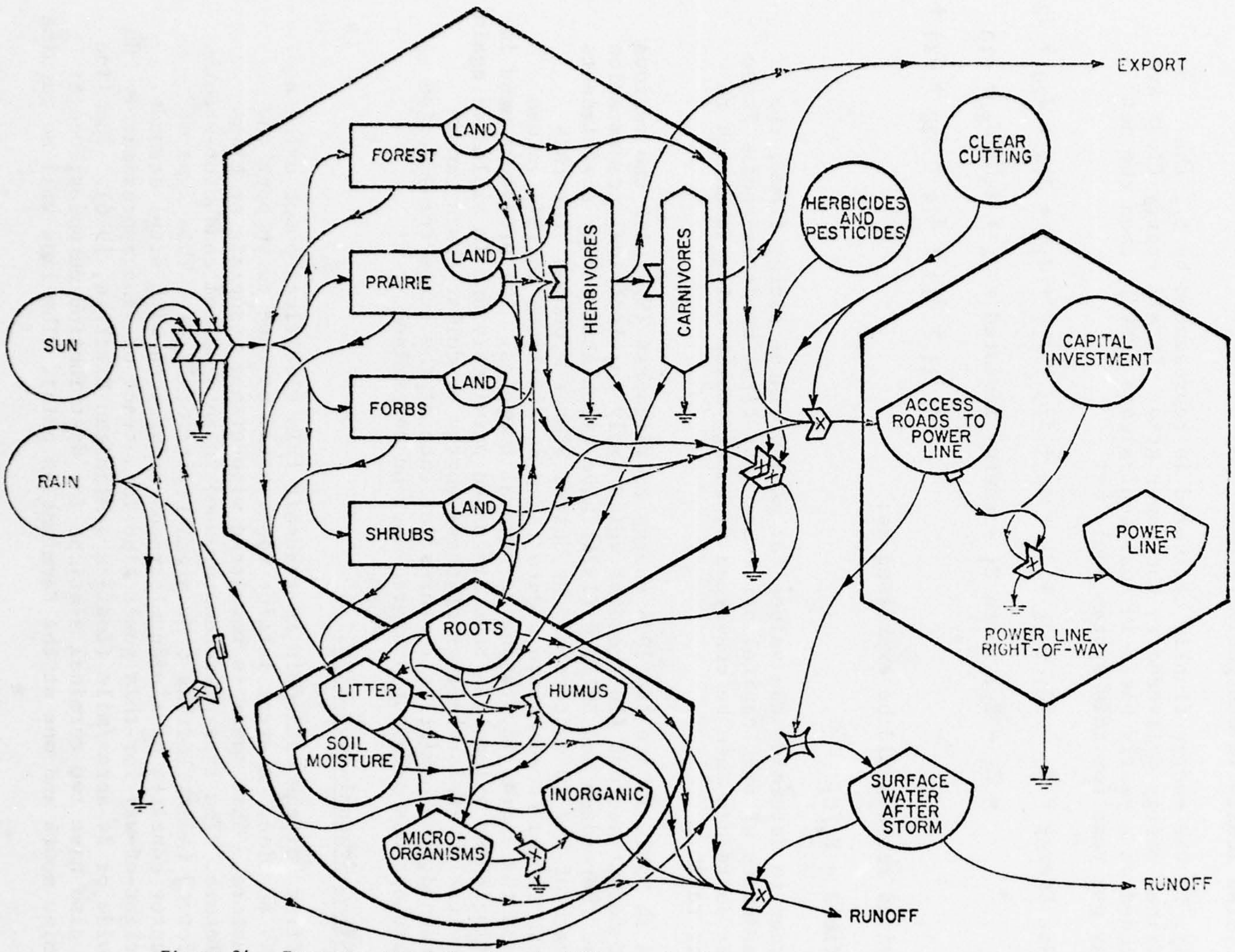

Figure 24. Ecosystem Model Showing the Effects of a Transmission Line on Nearby Ecosystems.

Other natural energy losses might also be included such as local geological disturbances. Further research is needed to evaluate all associated losses in energetic terms.

In Fig. 23 the energy finally delivered is represented by E_4, the electrical energy delivered to the power grid. If all energy flows are expressed on a yearly basis in coal equivalents (FFCE), then the net energy per year for this system would be:

$$\text{Net Energy} = E_4 - (J_1 + J_4 + J_5 + J_8 + J_{10} + J_{11} + J_{13} + J_{14} + J_{20} + J_{24})$$

$$= E_4 - E_1; \text{ where } E_1 = \text{energy invested} = J_4 + J_5 + J_8 + J_{10} + J_{11} + J_{13} + J_{14} + J_{20} + J_{24} + J_1$$

The yield ratio would be expressed as:

$$\text{Yield} = E_4/E_1$$

In order to determine the values for many of these energy flows, the dollar costs of each capital structure must first be determined. These dollar costs can then be converted to energy costs using an energy to dollar ratio.

Shown in Table 15 are the 1974 energy coefficients (E_j^T) for the various input-output sectors (IO sectors) which apply to electrical transmission lines. Herendeen and Bullard (1974) have calculated energy coefficients for each of 357 IO sectors of the United States economy. For this report, it was necessary to update these coefficients to 1974 values and add the energy inputs due to natural energies. The procedure used in updating these values has been discussed previously and is explained again in the table. Before either of these energy or dollar costs can be determined, the capital structures for each of the three transmission voltage options previously stated must be determined.

765-KV AC Transmission Line

The first voltage option is to transmit this electrical power using a 765-KV AC line. A steel lattice tower would be used to support the conductors. This tower is insulated with either porcelain or glass insulators. The type of conductor used is an aluminum conductor-steel reinforced (ACSR)(Indiana & Michigan Electric, 1976). This type of conductor consists of aluminum strands reinforced with steel strands. The right-of-way for this power line is a tract of land approximately 200 ft. wide or 24 acres/mile (Indiana & Michigan Electric, 1976). The line will also have two terminal stations for distribution purposes; one at the mine mouth and one at the termination point. The line will be running

Table 15
Energy Coefficients for Specific IO Sectors for 1974

Commodity & IO Sector	E_j(1967) BTU/$*	E_j(1974) BTU/$#**	E_j^T BTU/$#
Steel (IO 4004)	124,602	95,145	114,345[a]
Aluminum (IO 3808)	244,677	186,833	206,033[b]
Concrete (IO 3612)	180,661	144,207	163,407[c]
Porcelain (IO 3608)	74,685	59,615	78,815[d]
Glass (IO 3501)	102,999	82,215	101,415[e]
Term. Equip. (IO 5805) (IO 4905) (IO 5303) (IO 5301)	51,190	41,024	60,224[f]
Wholesale Trade (IO 6901)	35,651	27,794	46,994[g]
New-Const. (IO 1103)	79,610	64,888	84,088[h]
Maint. Const. (IO 1202)	57,108	46,547	65,747[i]
Hardware (IO 4203)	74,609	58,806	78,006
Labor			74,426

*(Herendeen & Bullard, 1974)

**This includes only fossil fuel energies used in economy.

#This ratio includes both fossil fuel and natural energy work in economy. See Table 3.
The ratio of natural energy to GNP for 1974 was 19,200 BTU/$ = E^N

$$E_j^T(1974) = E_j(1974) + E^N(1974)$$

$$E_j(1974) = E_j(1967) \times \frac{\text{Total Energy(1974) in BTU}}{\text{Total Energy(1967) in BTU}} \times \frac{\text{GNP(1967)}}{\text{GNP(1974)}} \times \frac{\text{Price Index(1967)}}{\text{Price Index(1974)}}$$

where E_j = Energy Coefficient in BTU/$
Total Energy in BTU = Total Energy input into U.S. Economy
GNP = Gross National Product in U.S. Econ. in constant dollars
Price Index = price index for each IO Sector

Footnotes to Table 15 (cont.)

Can also be written:

$$E_j(1974) = E_j(1967) \times \frac{\text{Energy}(1974)/\text{GNP}(1974)}{\text{Energy}(1967)/\text{GNP}(1967)} \times \frac{\text{Price Index}(1967)}{\text{Price Index}(1974)}$$

$$E_j^T(1974) = E_j(1974) + E^N$$

where E^N = Natural Energy input in 1974

a) $E_j^T = (124{,}602 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{131.4} + 19{,}200 \text{ BTU/\$} = 114{,}345 \text{ BTU/\$}$

b) $E_j^T = (244{,}677 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{131.4} + 19{,}200 \text{ BTU/\$} = 206{,}033 \text{ BTU/\$}$

c) $E_j^T(1974) = (180{,}661 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{125.7} + 19{,}200 \text{ BTU/\$} = 163{,}407 \text{ BTU/\$}$

d) $E_j^T(1974) = (74{,}685 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{125.7} + 19{,}200 \text{ BTU/\$} = 78{,}815 \text{ BTU/\$}$

e) $E_j^T(1974) = (102{,}999 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{125.7} + 19{,}200 \text{ BTU/\$} = 101{,}415 \text{ BTU/\$}$

f) $E_j^T(1974) = (51{,}190 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{135.7} + 19{,}200 \text{ BTU/\$} = 60{,}224 \text{ BTU/\$}$

g) $E_j^T(1974) = (35{,}651 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{128.7} + 19{,}200 \text{ BTU/\$} = 46{,}994 \text{ BTU/\$}$

h) $E_j^T(1974) = (79{,}610 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{123.1} + 19{,}200 \text{ BTU/\$} = 84{,}088 \text{ BTU/\$}$

i) $E_j^T(1974) = (57{,}108 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{123.1} + 19{,}200 \text{ BTU/\$} = 65{,}747 \text{ BTU/\$}$

j) $E_j^T(1974) = (74{,}609 \text{ BTU/\$}) \times \frac{126{,}690 \text{ BTU/\$}}{126{,}266 \text{ BTU/\$}} \times \frac{100.0}{127.3} + 19{,}200 \text{ BTU/\$} = 78{,}006 \text{ BTU/\$}$

at 75% of its total capacity to allow enough leeway to handle power surges and limited periods of heavy demand.

Shown in Table 16 are the estimated annual dollar and energy costs for this 765-KV AC line. Each dollar cost is multiplied by its corresponding energy coefficient to give the cost in terms of energy. Line losses and productivity losses are direct energy losses, and therefore have no corresponding dollar value or energy coefficient. Line loss is the power lost due to the resistance of the conductor and is a function of the power being transmitted over the line. The value for productivity losses is an average of three different ecosystems over which the power line was assumed to traverse. An average of the productivity of grass-lands and pastures, moist temperate forests, and fuel subsidized agriculture was calculated to be 1485 BTU (FFCE)/m^2/yr. (See Table 16, footnote h).

Figure 25 is a simplified diagram showing the various energy flows associated with a 765-KV AC line and their values. All values are taken from Table 16, with the exception of the transmission energy. This value was determined by assuming that power was determined at a 75% loading capacity and that the line losses were compensated throughout the line in order to keep the voltage at its rated value. This additional energy input was included. All the losses and costs are summed at the bottom of Fig. 25. Terminal losses were not included because such data was not available. The energy yield ratio is computed by dividing the energy delivered to the power grid at the line's destination, by the total amount of energy invested in the line. This total amount of energy invested also includes line losses and losses due to ecosystem destruction. The energy delivered to the power grid minus energy costs and energy losses results in the net energy of the system.

± 400-KV DC Transmission Line

The second voltage option is to transmit this electrical power using a ± 400-KV DC line (DC power is transmitted with one pole, or conductor, negative to earth and one pole positive to earth. The full voltage rating of the line is the voltage difference between the two poles). A steel lattice tower would be used to support an ACSR conductor as with the 765-KV AC line. The insulator used will be a porcelain insulator, and the right-of-way will consist of a tract of land 160 ft. wide or 19 acres/mile (BPA, 1970). The line will also consist of two converter stations, one located at each end of the line. These stations convert AC power to DC power and vice versa. The line will operate at a capacity of 1400 MW (BPA, 1976). Shown in Table 17 are the estimated annual dollar and energy costs for this line. Terminal losses are a direct energy loss due to the conversion of one type of electrical power to another.

Table 16

Estimated Annual Dollar and Energy Costs for a 1,000-mile 765-KV AC Power Transmission Line*

Parameter	(A) Dollar Cost**	(B) E_j^{T} #	(C) Energy Cost ## in x 10^9 BTU
Steel Towers	2.10×10^6	114,345	240
Concrete Foundations	5.50×10^5	163,407	89.9
Conductor	1.4877×10^6		281.1
81.4% AL	1.211×10^6 [a]	206.033	
18.6% Steel	2.767×10^5	114,345	
Alumoweld Groundwire	4.28×10^4	206,033	8.82
Insulators & Hardware	3.40×10^5	78,410[b]	26.7
Misc. Material	1.05×10^4	60,224[c]	.632
Labor	1.9474×10^6	74,426[d]	145
Clearing Right of Way	1.544×10^5	74,426	11.49
Stores Expense[e]	4.53×10^4	46,994	2.13
Construction Damages	2.212×10^4	65,747	1.45
Terminals	2.588×10^6 [f]	60,224	15b
Overheads	2.4962×10^6	74,426[d]	186
Line Losses			20370[g]
Productivity Losses			144[h]

*System lifetime assumed to be 50 yrs (BPA, 1976)

**(Indiana & Michigan Electric, 1976) unless otherwise noted

#(See Table 15)

##Column (C) = Column (A) x Column (B)

a) $(\$1.4887 \times 10^6)(81.4\%) = \$1.211 \times 10^6$

b) $\dfrac{\text{Porcelain + Hardware}}{2} = \dfrac{78{,}815 \text{ BTU/\$} + 78{,}006 \text{ BTU/\$}}{2} = 78{,}410 \text{ BTU/\$}$

Footnotes to Table 16 (cont.)

Estimated Annual Dollar and Energy Costs for a 1,000-mile 765 KV AC Power Transmission Line*

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c) E_j^T for terminal equipment (see Table 15)

d) See Table 15. The ratio of fossil fuels + natural energies to GNP in 1974 was approximately 18,700 kcal/dollar = 74,426 BTU/dollar.

e) Stores expense is the cost incurred for storing materials used on the line.

f) (BPA, <u>Celilo</u>)

g) Overn, 1975)

$$\frac{(1.84 \times 10^5 \text{ j/s/mile})(1000 \text{ mi})(365 \text{ days/yr})(86400 \text{ s/day})\left(\dfrac{3.7 \text{ Fossil Fuel Equivalents}}{\text{Unit of Electrical Energy}}\right)}{1054 \text{j/BTU}}$$

$$= 20370 \times 10^4 \text{BTU/yr}$$

(See Table 2 and Fig. 3c for conversion of electrical energy to fossil fuel equivalents.)

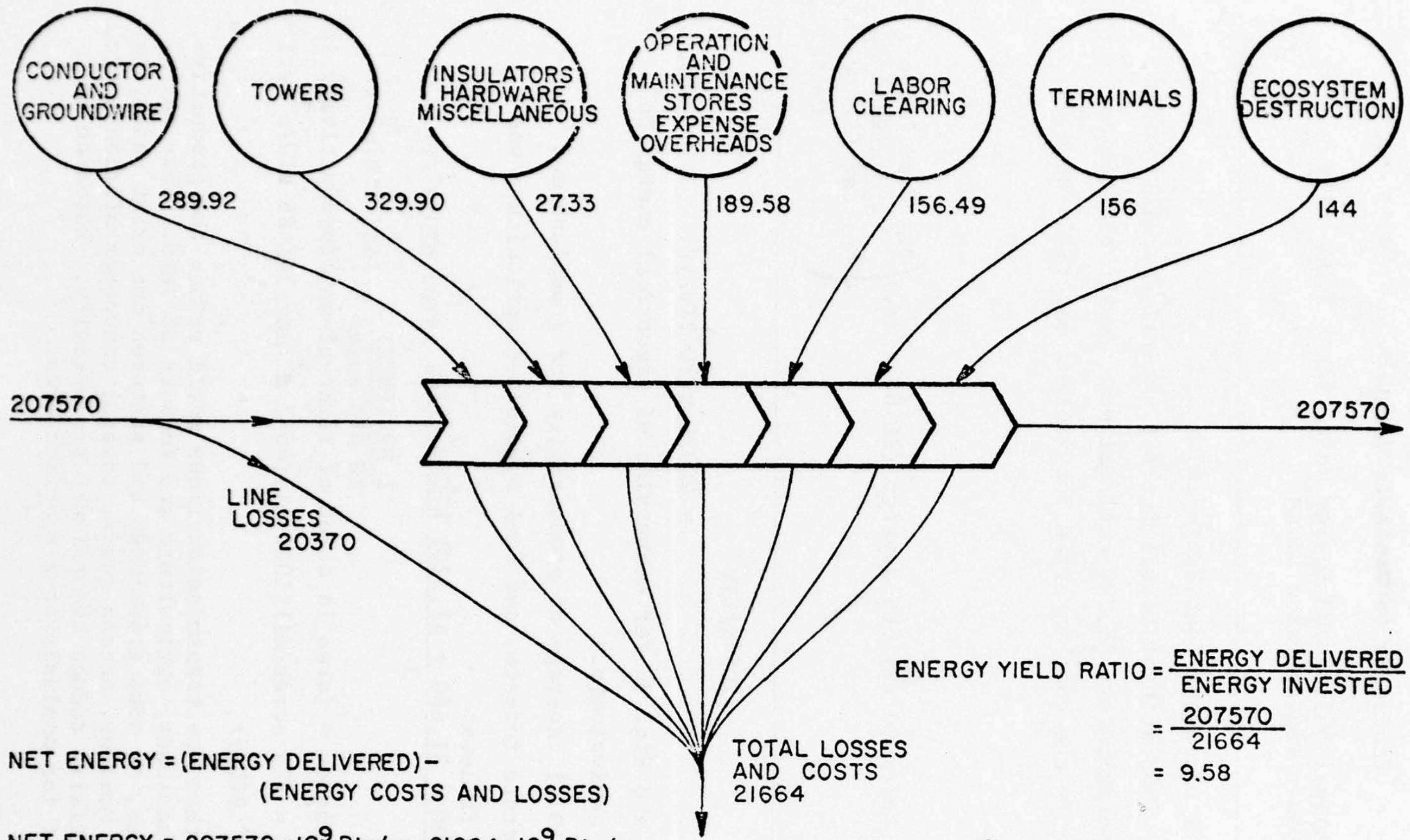
h) (Odum, E.P., 1971) Average of productivity for grassland and pasture, temperate forests, and fuel subsidized agriculture was calculated as follows:

$$\text{Average} = \frac{(9900 + 31{,}680 + 47{,}520) \text{ BTU/m}^2\text{/yr}}{3} = 29700 \text{ BTU/m}^2\text{/yr} \times \frac{1 \text{ BTU(FFCE)}}{20 \text{ BTU sugar}} = 1485 \text{ BTU/m}^2\text{/yr}$$

Productivity Losses = (area in acres of right-of-way)(productivity in BTU/m^2/yr) = (24 acres/mi)(1000 mi)(4047 m^2/acre)(1485 BTU/m^2/yr) = 1.44×10^{11} BTU/yr

This assumes that the transmission lines would reduce the productivity of the grasslands, agriculture and forests to zero. This may not be the case, as some grasslands and pastures can exist under the power lines. However, access roads, towers, converter stations, etc, would substantially reduce the primary productivity. Research is needed here if for analysis of a specific area.

CALCULATIONS OF ENERGY YIELD TO ENERGY COSTS FOR A 765-KV AC POWER LINE. *



$$\text{ENERGY YIELD RATIO} = \frac{\text{ENERGY DELIVERED}}{\text{ENERGY INVESTED}} = \frac{207570}{21664} = 9.58$$

NET ENERGY = (ENERGY DELIVERED) − (ENERGY COSTS AND LOSSES)

NET ENERGY = 207570×10^9 Btu/yr − 21664×10^9 Btu/yr .

NET ENERGY = 185906×10^9 Btu/yr = 1.86×10^{14} Btu/yr

* − ALL VALUES $\times 10^9$ Btu/yr

Figure 25. Major Costs Associated with a 765-KV AC Power Line

Table 17

Estimated Annual Dollar and Energy Costs for a 1,000-mile ± 400-kv DC Power Transmission Line*

Parameter	(A) Dollar Cost**	(B) E_j^T $\frac{(BTU)}{\$}$ #	(C) Energy Cost $\times 10^9$ $\frac{BTU}{yr}$ ##
Steel Towers	$\$1.63 \times 10^5$ [a]	-14,345	18.6
Conductor[b]	$\$7.64 \times 10^5$ [c]		144.
81.4% AL	$\$6.22 \times 10^5$ [d]	206,033	
18.6% Steel	$\$1.42 \times 10^5$ [e]	114,345	
Steel Groundwire	$\$1.60 \times 10^2$	114,345	0.018
Porcelain Insulator	$\$4.59 \times 10^3$	78,815	0.362
Converter Stations	$\$2.10 \times 10^6$ [g]	60,224[i]	126.
Misc. Material	$\$7.53 \times 10^4$	60,224[i]	4.54
Oper. & Maint.	$\$2.20 \times 10^6$ [h]	64,847	143.
Stores Expense	$\$1.58 \times 10^5$	46,994	7.44
Labor (includes clearing)	$\$9.79 \times 10^4$	74,426	7.30
Overhead	$\$4.59 \times 10^5$	74,426	34.2
Line Losses			15240[j]
Terminal Losses			3563[k]
Productivity Losses			114[l]

*System lifetime assumed to be 50 years (BPA, 1976).

**(BPA, 1976) unless otherwise noted

#See Table 15

##Column (C) = Column (A) x Column (B)

a) (30 tons/mi)(1,000 mi) = 30,000 tons

(30,000 tons)(2,000 lb/ton)($13.615/100 lbs)/50 yrs = $\$1.63 \times 10^5$

b) total length = length of power line + extra length to account for sag between towers

Footnotes to Table 17 (cont.)

= length of power line + (0.01)(lenght of power line)

= [1,000 mi + (0.01)(1,000 mi)](5280 ft/mi)

= 5.3328×10^6 ft

c) (5.3328×10^6ft)(\$1.79/ft)(4 conductor wires)/50 yrs = 7.64×10^5

d) (\$$7.64 \times 10^5$/yr)(0.814) = \$$6.22 \times 10^5$/yr

e) (\$$7.64 \times 10^5$/yr)(0.186) = \$$1.42 \times 10^5$/yr

f) Tower spacing = 1150 ft $\quad \frac{(1{,}000\text{mi})(5280\text{ ft/mi})}{1150\text{ ft}}$ = 4592 towers

(2 insulators/tower)(4592 towers) = 9184 insulators

(9184 insulator)(\$25/insulator)/50 yr = \$$4.59 \times 10^3$/yr

g) $\left(\frac{\$35 + \$40}{2}\right.$ /kw/terminal)(1.4×10^6kw)(2 terminals)/50 yrs

= \$$2.0 \times 10^6$/yr

h) (BPA, 1975)

i) E_j^T for terminal equipment (see Table 15)

j) Line Losses = $\left(\frac{\text{Power}}{\text{Voltage}}\right)^2$ (D-C resistance/mi/pole)(2 poles)

(distance in mi) = $\left(\frac{1400\text{MW}}{800\text{KV}}\right)^2$ (0.0225Ω)(1,000 mi)

= 138 MW = 1.38×10^8W

1.38×10^8W = (1.38×10^8j/s)

Energy Lost = (1.38×10^8j/s)(50 yrs)(365 days/yr))(86,400 s/day)

(1054 j/BTU) $\left(\frac{\text{3.7 fossil fuel equiv.}}{\text{unit of elect. energy}}\right)$ = $7.62\text{x}10^{14}$BTU for 50 years

Energy Lost/Year = 7.62×10^{14}BTU/50 yrs

= 1.524×10^{13}BTU/yr

Footnotes to Table 17 (cont.)

k) $\dfrac{\text{Terminal Losses}}{\text{Year}}$ =

$$\frac{\left[\frac{(0.01+0.013)}{(2)}\right] (2 \text{ terminals}(4.415\text{x}10^{16} \text{j/yr}) \left(\frac{3.7 \text{ fossil fuel equiv.}}{\text{unit of elect. energy}}\right)}{1054 \text{ j/BTU}}$$

$= 3.563 \times 10^{12}$ BTU/yr

$= 3563 \times 10^{9}$ BTU/yr

l) Average productivity obtained from footnote h, Table 16.

Productivity Losses = (average productivity in BTU/m^2/yr)
(area of right-of-way = (1485 BTU/m^2/yr(19 acres/mi)(1000 miles)
(4047 m^2/acre) = 1.14×10^{11} BTU/yr

Figure 26 is a simplified diagram of the energy flows associated with a ± 400-KV Dc power line. The total energy costs and losses are summed at the bottom of the figure, and calculated energy yield ratio and net energy are shown.

± 600-KV DC Transmission Line

The third and final option is to transmit this power using a ± 600-KV DC power transmission line rated at 2200 MW (BPA, 1976). A steel lattice tower would be used to support an ACSR conductor (BPA, 1976). As with the ± 400-KV DC line, these towers will be insulated with porcelain insulators. The right-of-way for this line is a tract of land 160 ft. wide (BPA, 1970) or an acreage of 19 acres/mile. Two converter stations are also necessary to convert the AC power generated by the power plant to DC power, and DC power back to AC power at the line's destination. Table 18 shows the estimated annual dollar and energy costs associated with this power line. Once again, line losses, terminal losses, and natural productivity losses are direct energy losses and therefore have no corresponding dollar values and energy coefficients.

Figure 27 is a simplified diagram showing the various energy flows associated with a ± 600-KV DC power transmission line. Also shown in the figure is the calculation for the energy yield and net energy for this line.

Comparison of Alternative Transmission Systems

Table 19 is a summary of the energy yield ratios and net energies for the three voltage options studied. These calculations include the voltage options of towers, conductors, and insulators, as well as the terminals and converter stations. As can be seen from the table, a ± 600-KV DC power transmission line gives the highest energy yield ratio and also the greatest amount of net energy. On this basis alone, it can be stated that the option of transmitting electrical power by way of a ± 600-KV DC transmission line is the most energetically feasible. For more accurate results, however, a more detailed study of these three options would have to be conducted using a site specific analysis.

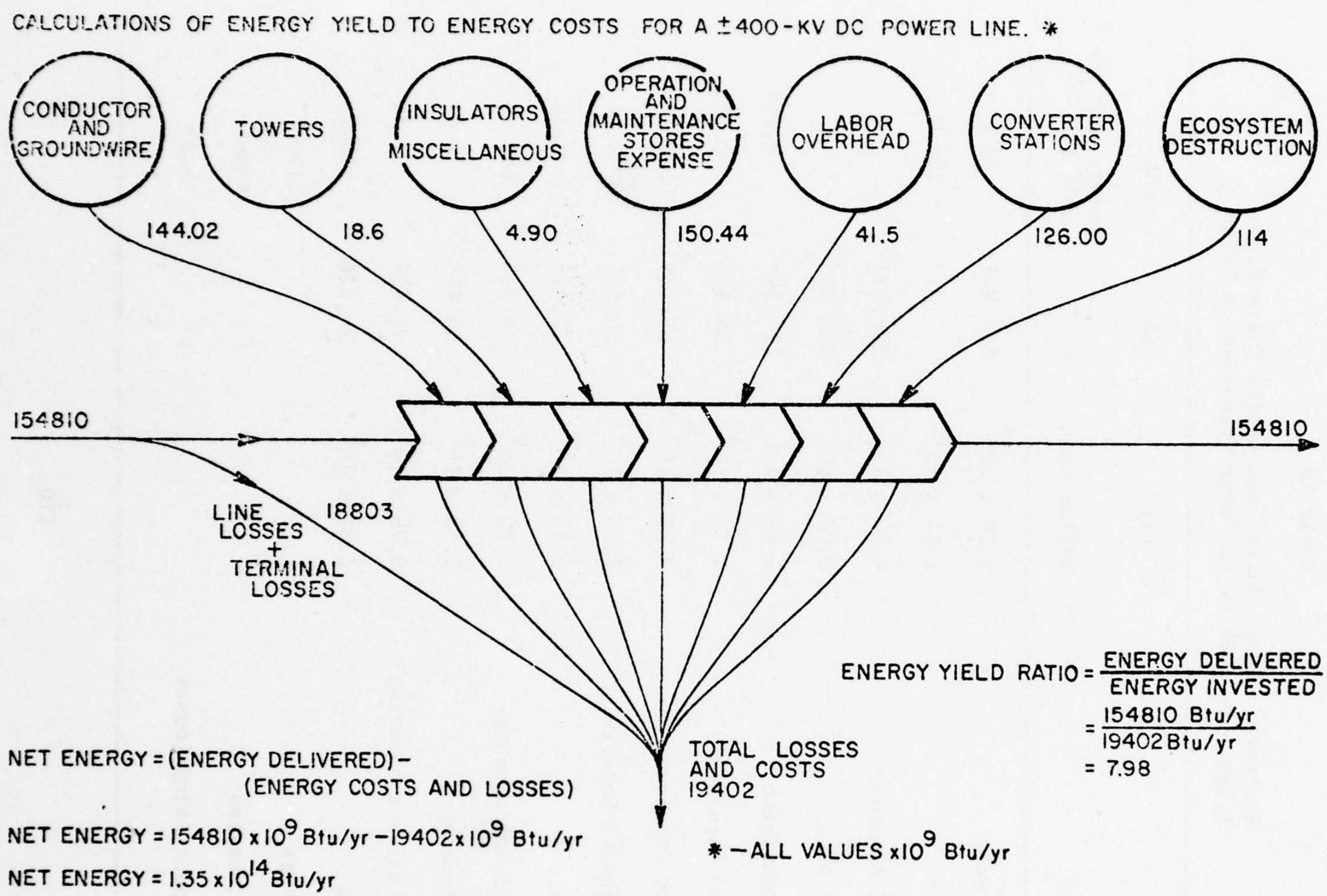


Figure 26. Major Costs Associated with a $\pm$ 400-KV DC Power Line

Table 18

Estimated Annual Dollar and Energy Costs for a 1,000-mile ±600 KV DC Power Transmission Line*

Parameter	(A) Dollar Cost	(B) $E_j T$#	(C) Energy Cost in x10^9 BTU ##
Steel Towers	2.29×10^5 [a]	114,345	26.2
Conductor	1.14×10^6		216.0
81.4% Aluminum	9.32×10^5	206,033[c]	
18.6% Steel	2.08×10^5	114,345	
Steel Groundwire	1.60×10^2	114,345	0.018
Porcelain Insulator	4.59×10^3	78,815	0.362
Converter Stations	3.30×10^6 [b]	60,224[d]	199
Miscellaneous Material	7.53×10^4	60,224	4.54
Land Costs	1.14×10^5	74,426	8.48
Oper. and Maintenance	2.20×10^6	64,747	145
Stores Expense	1.58×10^5	46,994	7.44
Labor (includes clearing)	9.79×10^4	74,426	7.30
Overhead	4.59×10^5	74,426	34.2
Line Losses			14170[e]
Terminal Losses			5590[f]
Nat. Productivity Losses			114[g]

Footnotes to Table 18

Estimated Annual Dollar and Energy Costs for a 1,000-mile $\pm$600-KV DC Power Transmission Line*

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*System lifetime assumed to be 50 yrs (BPA, 1976)

**(BPA, 1976) unless otherwise noted

#See Table 15

##Column(C) = Column(A) x Column (B)

[a]Tower Cost =(42 ton/mi)(1,000 mi)(2,000 lb/ton)($13.615/100 lb) = $2.29 x 10^5/yr.

[b] $\frac{(\$35 + \$40/KW/terminal)}{2}(2.2 \times 10^6$ KW/2 terminals/50 yrs) = $3.30 x 10^6/yr

[c]See Table 16, footnote b.

[d] E_j^T for terminal equipment (See Table 15)

[e]Line losses = $\left(\frac{\text{Power in MW}}{\text{Voltage in KV}}\right)^2$ (resistance in ohms/mi/pole)(2 poles)

$\times$ (distance in mi) = $\left(\frac{2200\ \text{MW}}{1200\ \text{KV}}\right)^2$ $(0.019\Omega)(2)(1{,}000\ \text{mi}) = 128$ MW

(BPA, 1976)

Energy Lost/yr =

(128 MW)(365 days/yr)(86,400 s/day) $\frac{\text{3.7 fossil fuel equiv.}}{\text{unit of elect. energy}}$

x (1054 j/BTU) = 1.417 x 10^{13} BTU/yr

[f]Terminal losses (BPA, 1976) =

$$\frac{\frac{(0.01 + 0.013)}{2}(2\ \text{term})(6.94 \times 10^{16}\ \text{j/yr})\ \frac{\text{3.7 fossil fuel equiv.}}{\text{unit of elect. energy}}}{(1054\ \text{j/BTU})}$$

= 5.59 x 10^{12} BTU/yr

[g]See footnote 1, Table 17.

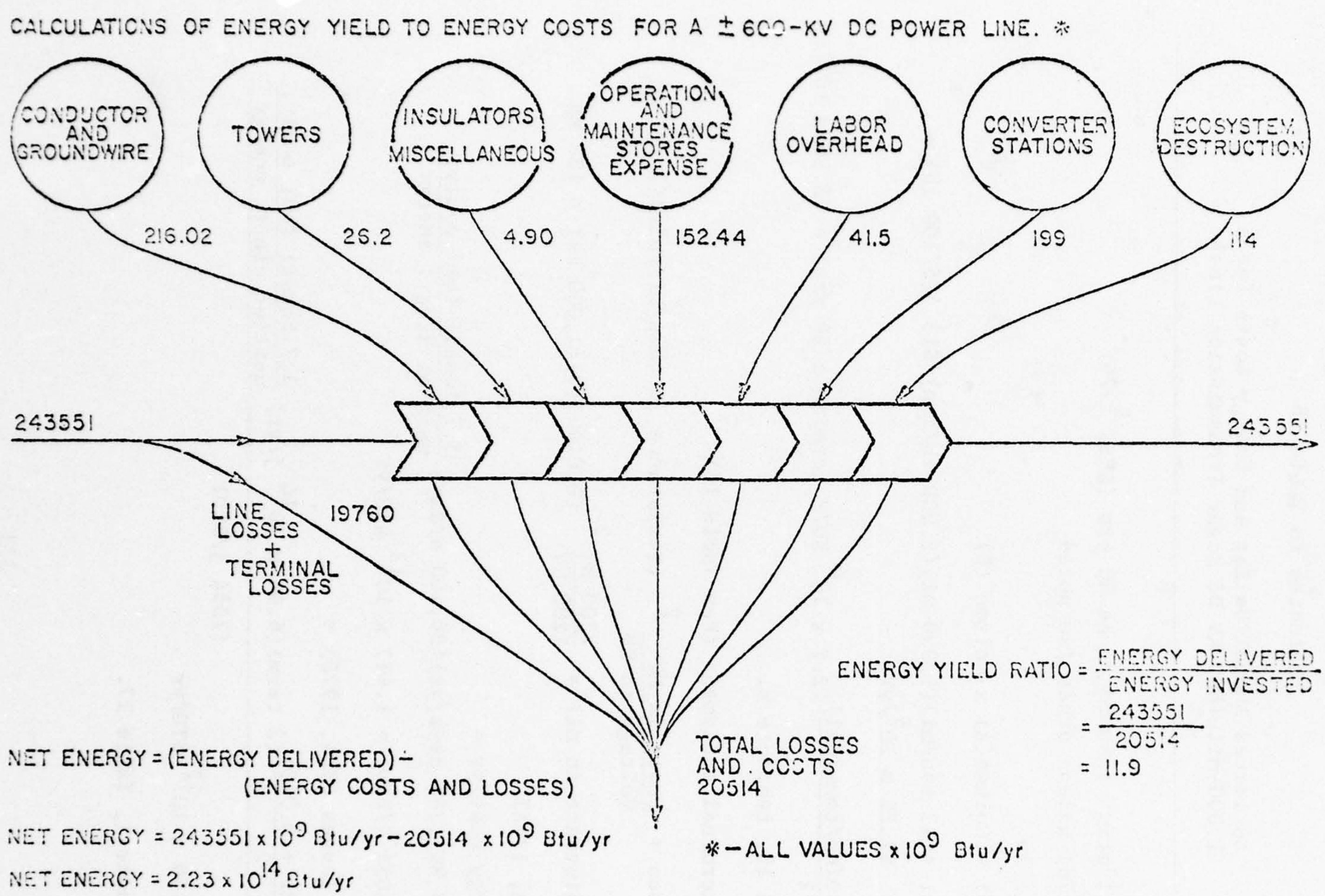

Figure 27. Major Costs Associated with a ± 600-KV DC Power Line

Table 19

Summary of Energy Yield Ratios and Net Energies for the Three Voltage Options

Transmission System	Energy Yield Ratio *	Net Energy** $\times 10^{14}$
765 KV-AC	9.58	1.86
$\pm$400 KV-DC	7.98	1.35
$\pm$600 KV-DC	11.9	2.23

*As mentioned in previous paragraphs this is the ratio of energy transmitted per year to total energy cost per year.

**This is energy transmitted minus *total* energy costs.

E. Summary of Results for Barge, Railroad, Pipeline and High Voltage Transport Systems

This section summarizes the results of the energy analysis conducted for barges, railroads, pipelines and electrical transmission lines in sections III-A to III-D. It should be kept in mind that these analyses are not the last word on the energy costs of the systems because many approximations have been made in the absence of required data. This report showed how such analyses can be made provided that the research and manpower are available. There also exists a wide range of energy costs/ton-mile because of the variability of individual transportation routes. The range of energy costs per ton-mile are summarized in Table 20 for barges, railroads, and pipelines. Also included in Table 20 is the energy cost per ton-mile for electrical transmission lines where the tons shipped were calculated by finding the amount of coal necessary to produce the electricity transmitted. The direct energy cost refers to energy required for operation (in the case of the transmission line it is equivalent to the energy loss along the line). The indirect energies are those associated with capital investment, goods, labor, and natural system destruction.

The wide variation of costs in Table 20 are attributable to several factors. The high indirect energy costs of pipelines are attributable to the energy costs of building a new pipeline. Those indirect costs associated with building new track for unit train operation significantly increase the costs of coal shipment by train. The high costs of electrical transmission are attributable to the energy losses along the transmission line, while the indirect costs of goods, services, and natural system destruction are relatively small. The costs of a 1000-mile pipeline system were extrapolated from data for a 273-mile pipeline. This may not be a good assumption because a 1000-mile pipeline would probably have a larger diameter.

If these calculations are fairly accurate, then the dedicated "tow" would be the best energetically. Government subsidies were included in this analysis, but the data supplied by Federal Barges Lines may represent an abnormally efficient case. If a barge operates under "average" conditions, then unit train operation is energetically cheaper. The results obviously depend on specific localities, distances, and commodities transported, but energetic analysis could be conducted for other cases. Future construction required for the Corps of Engineers may decrease barge yield ratios, but further research will be required to assess this impact.

As outlined under the section on spatial energy theory in section II-A, the energy yield ratio (energy delivered divided by energy costs)

Table 20

Summary of Energy Costs for Barge, Railroad, Pipeline and High Voltage Transport Systems for Coal Transportation*

	(A) Direct Energy Cost, BTU per ton-mile	(B) Indirect Energy Cost, BTU per ton-mile	(C) Total Energy Cost, BTU per ton-mile	Energy Yield Ratio for 1000 mile transport
Barge Transport Dedicated Tow	249	88.3	397.3[a]	50.4[b]
Average Conditions	680	349.3	1029.3[c]	19.4[d]
Railroad Transport Unit Train	400	122.6	522.6[e]	39.0[f]
Unit Train with New Track	400	2722.6	3122.6[g]	6.45[h]
Coal Slurry Pipeline	---	---	755[i]	25.8[j]
Electrical Transmission ($\pm$ 600 KV DC)	6003	229	6232[k]	11.9[l]

*See sections III-A to III-D for detailed analyses of these systems. Direct energy is fuel consumed in operation. Indirect energy costs are those associated with capital investment, goods, labor, and natural system destruction. Total energy costs are the sum of columns (A) and (B). Energy yield ratio is (coal energy delivered÷energy cost to deliver) for the transport of coal a thousand miles.

[a]This number calculated based on data from Federal Barge Lines, Inc. (See Table 6).

[b]See Table 7.

[c]This number calculated based on average data for the Inland Waterway System (See Table 5).

Footnotes to Table 20 (cont.)

Summary of Energy Costs for Barge, Railroad, Pipeline and High Voltage Transport Systems for Coal Transportation*

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[d]See Table 7.

[e]This is calculated for unit train on existing track (See Table 8).

[f]See Fig. 19a.

[g]Based on unit train operation with installation of a thousand miles of new track. The energy cost of new track is (see Fig. 19b):

$$1.3 \times 10^{12} \text{ BTU}/500{,}000 \text{ tons} \times 1000 \text{ miles} = 2600 \text{ BTU/ton-mile}$$

Adding this to the costs of 511.8 BTU/ton-mile for a unit train gives 3111.8 BTU/ton-mile.

[h]See Fig. 19b.

[i]See Table 14. Data extrapolated from 273-mile pipeline design.

[j]See Table 14.

[k]See Fig. 27. Electrical energy transmitted was:

$$243551 \times 10^{9} \text{ BTU} = 12.18 \times 10^{6} \text{ tons of coal}$$

if it is assumed that coal has a heating value of 10,000 BTU/lb.
Ton-miles is then 12.18×10^6 tons x 1000 miles = 12.18×10^9 ton-miles

Direct energy losses are the line losses

$$= \frac{19760 \times 10^{9} \text{ BTU of electrical}}{12.18 \times 10^{9} \text{ ton-miles}} \times \frac{3.7 \text{ BTU coal}}{1 \text{ BTU electrical}} = 6003 \text{ BTU/ton-mile}$$

Energy costs of capital, labor, and natural system destruction are

$$\frac{754 \times 10^{9} \text{ BTU of electrical}}{12.18 \times 10^{9} \text{ ton-miles}} \times 3.7 = 229 \text{ BTU/ton-mile}$$

Total costs = 6003 + 229 = 6232 BTU/ton-mile

[l]See Fig. 27.

as a function of distance is desirable in order to evaluate the energetic competitiveness of fossil fuel resource regions. Figure 28 plots the energy yield ratio as a function of distance for the transport of coal by barge, railroad, slurry pipeline, and electrical transmission based on calculations in sections III-A to III-D.

This ratio was calculated by first determining the energy being transported by a unit train, a 15 barge tow, a pipeline and a $\pm$600 KV DC transmission line, as outlined in sections III-A to III-D. The energy cost of transporting this coal a given distance was then calculated using the energy cost/ton-mile or the energy cost per mile. The ratio of the energy delivered to the energy cost is the energy yield ratio. Obviously, the further the coal is transported, the higher the energy costs and the lower the yield ratio. The energy transmitted by the power line was converted to an equivalent energy value of coal for comparison to the other modes of transport. The footnotes to Fig. 28 explain the methods of calculation.

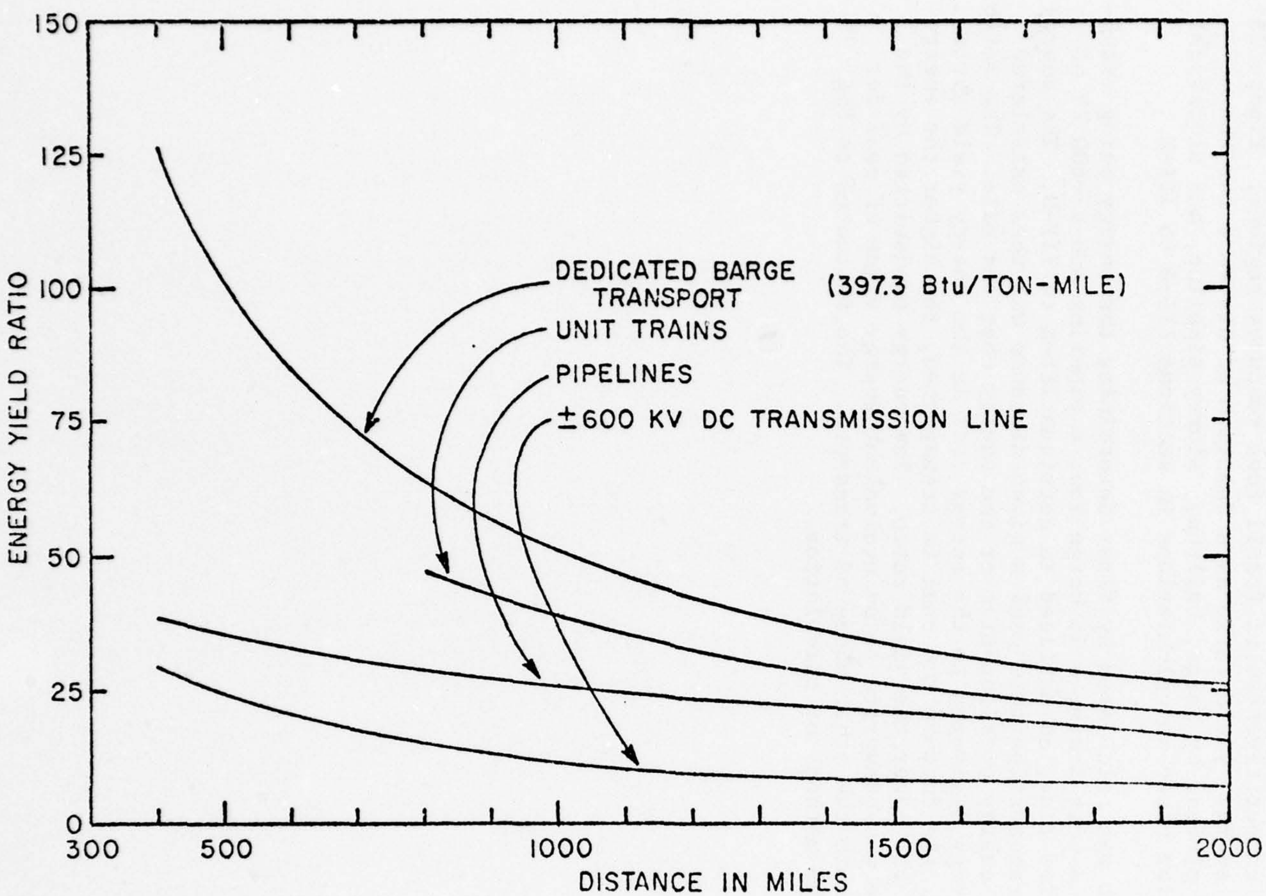


Figure 28. Summary Diagram of Energy Yield Ratio as a Function of Distance for Barges, Railroads, Pipelines and Electrical Transmission Lines for the Transportation of Coal. Energy yield ratio is the ratio of the energy of the coal transported to the energy cost of transporting this coal a given distance. The footnotes following the figure explain the assumptions.

Footnotes to Figure 28

1. It was assumed that the energy cost of barge transport remained constant at 397.3 BTU/ton-mile. Multiplying by the number of tons (23280) times the distance travelled will give the energy cost for a particular distance. Dividing this into the energy value of the fuel gives the yield ratio. The coal carried by 15 barges is 23280 tons or 4.66×10^{11} BTU.

2. See Fig. 18b for railroad graph.

3. Calculations for transmission line assumed a constant cost per mile for ± 600 KV DC line (See Table 18). The cost per mile is 20514×10^9 BTU/1000 miles/yr = 20514×10^6 BTU/mile/yr. Multiplying by the length of line gives the cost for a given distance. The energy transmitted is 243551×10^9 BTU/yr (see Fig. 27). The yield ratio is obtained by dividing the energy transmitted by the cost for a given length of line.

4. For pipeline calculations the fixed cost associated with slurry preparation and dewatering plants for a 273-mile pipeline was

$$171.18 \times 10^{10} \text{ BTU/yr}$$

The variable costs are attributed to the pipeline and pump stations. For a 273-mile pipeline this was

$$\frac{59.12 \times 10^{10} \text{ BTU/yr}}{273\text{-miles}} = 2.17 \times 10^9 \text{ BTU/yr/mile}$$

As an example, to calculate the energy yield ratio for 1000 miles:

$$\text{Energy transmitted} = 5 \times 10^6 \text{ tons/yr} \times \frac{10{,}000 \text{ BTU}}{\text{lb}} \times \frac{2000 \text{ lbs}}{\text{ton}}$$

$$\text{Energy transmitted} = 1 \times 10^{14} \text{ BTU/yr}$$

$$\text{Energy cost} = 171.18 \times 10^{10} \text{ BTU/yr} + 2.17 \times 10^9 \text{ BTU/yr/mile} \times 1000 \text{ miles}$$

$$\text{Energy cost} = 3.88 \times 10^{12}$$

$$\text{Energy yield ratio} = \frac{1 \times 10^{14}}{3.88 \times 10^{12}} = 25.8 \text{ for 1000 miles}$$

CHAPTER IV
NORTHERN GREAT PLAINS SIMULATION MODEL FOR ILLUSTRATING SYSTEMS MODELING TECHNIQUES

The energy analyses of different transportation modes which have been presented thus far in this report have demonstrated the use of energy analysis on a static basis. Many complex problems, however, are best understood by studying them in a dynamic sense. Energy analysis specifically lends itself to studying dynamic processes since the symbols used in the conceptualization of systems models translate directly into a mathematical form used in computer simulations. It is the purpose of this section to demonstrate energy systems analysis with a computer simulation to determine the environmental and economic impacts on a geographic region. Due to the limited nature of the research project, the model described in this section is not considered to be sophisticated enough for adequate prediction. However, the intention of this section is to present the basic approach by which any dynamic model could be constructed. To this end a mathematical model was formulated from an energy diagram and simulated to demonstrate the methodology involved in dynamic energy systems analysis (Grasslands Biome Program, 1976). Due to the limited nature of the present report, extensive data has not been collected or measured for creating an accurate, predictive model.

The Northern Great Plains was chosen for simulation since it is an area about to undergo extensive coal development. Some 91.6 million acres of Montana, Wyoming, North Dakota, South Dakota, and Nebraska contain roughly 60% of the nation's mineable coal reserves. The region is represented in energy language in Fig. 29. The transport modes, shown within the dotted lines at the bottom of the model, are of critical importance to the model since in terms of both money and energy, transportation costs far exceed the costs involved in the mining process. Thus it is necessary that different modal-split scenarios be looked at carefully to obtain the best overall transport system. For the present simulation only unit train rail transport was considered. Submodels could easily incorporate partial rail transport with some on-site electrical power generation or any other combination of modes that were deemed of interest. Thus, a model of this type could help local decision-makers to make decisions between alternative transportation systems.

As can be seen from the model in Fig. 29, the mining company mines a certain number of tons of coal per year. This rate is determined using Coal Development Plan II (CDP II) as projected by the Northern Great Plains Resource Program (NGPRP). The acreage of

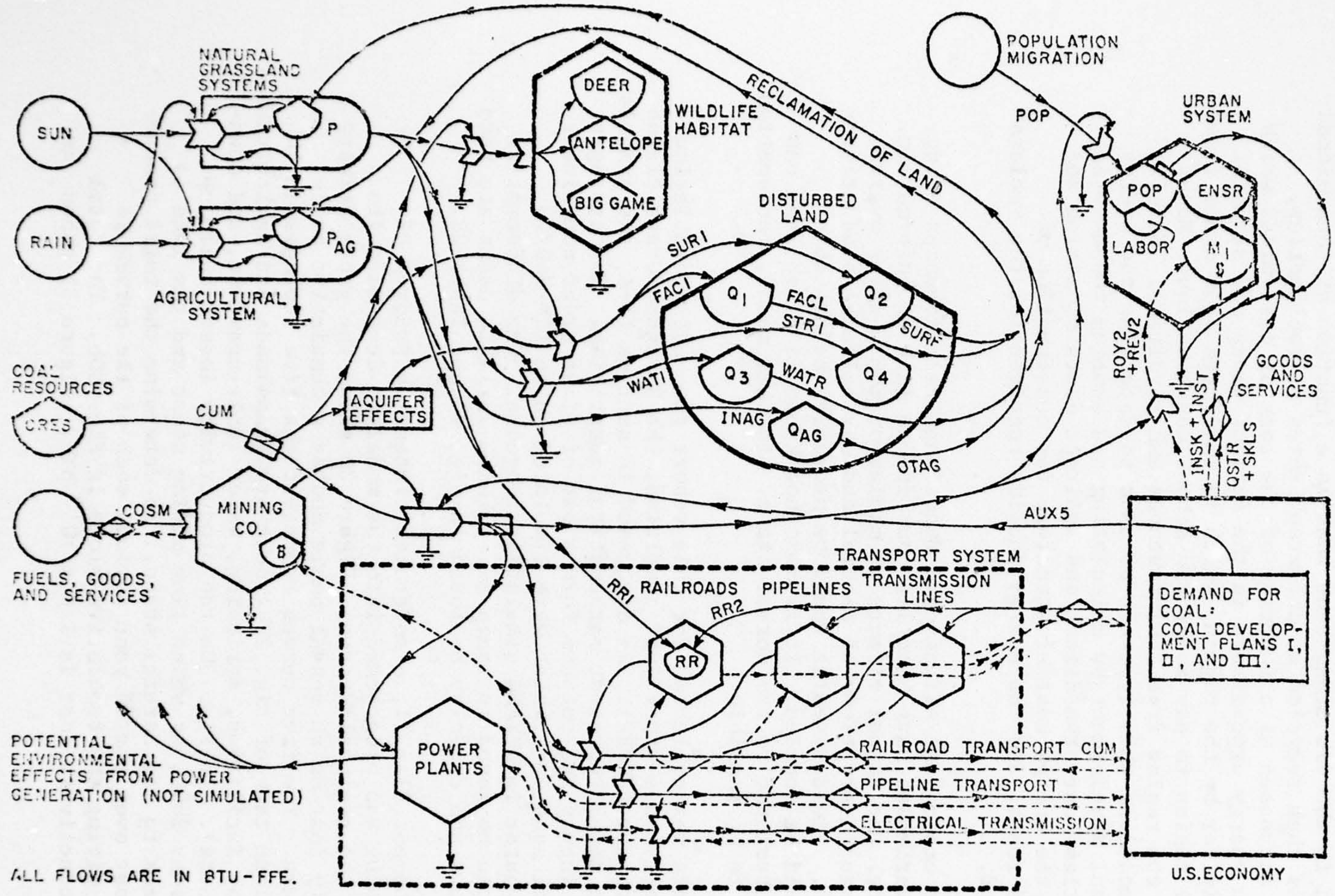


Figure 29. Energy Systems Diagram used for Simulating Effects of Coal Development on the Northern Great Plains (All flows in BTU--FFE). See Table 22 for explanation of variable names.

grassland and agricultural land is rendered nonproductive and is accumulated in the disturbed land tank as a function of tons mined. This land is then recycled at different rates of reclamation. Population increases as a function of the tons of coal mined which requires an energy expenditure in the form of raods and schools. This is paid for by the region, which is indicated by a money flow leaving the region to pay roads and school construction. Money flows into the region from coal revenues and royalties. Briefly stated, a model of this type can be used to determine the energy costs of coal development by calculating and summing the natural productivities lost, the direct and indirect costs of mining and transport, the energy cost of structure for construction of schools and roads, and the energy subsidy required for the reclamation of land.

Many of the ecological effects and functional relationships among the state variables have been left out due to lack of information. For instance, the actual effects of mining on the aquifer system and consequent disruptions of natural and agricultural productivity are unknown. Field research would be necessary before this process could be modeled. It is also not known if mined land can in fact be restored to its normal state. In this model, reclamation is assumed to be possible.

Since no data was collected for this report the model formulation relied heavily on a study just completed, the Northern Great Plains Resource Program (NGPRP). As discussed in section II-A, the symbols used in the model represent mathematical quantities. The storages with their inputs and outputs form a set of first order non-linear differential equations which were simulated on an IBM 360/70 digital computer in DYNAMO simulation language. The differential equations can be found in Table 21. DYNAMO variable names are used for the flows and can also be found in Fig. 29 and Table 22.

Coal Development Plan II, a moderately intensive program of surface mining was programmed into the model to determine its effects on the regional system. Figure 30 shows the gross primary productivity lost on an annual basis and on a cumulative basis over 60 years. The five curves represent the five storages in the disturbed land tank of Fig. 29 (these are grasslands and agriculture disturbed by facilities, stripping, water table drawdown, and downstream effects). In Fig. 30a the productivity losses build up until the year 2000, at which time mining stops and the land is recycled back to its natural state. To determine the total productivities lost over the 60 year period, each of the curves is integrated giving the cumulative plots in Fig. 30b. The total primary productivity lost is 1.8×10^{13} BTU. Figure 31 shows the

Table 21

Differential Equations for Northern Great Plains Simulation Model*

$$\dot{P} = FACL + SURF + STRM + WATR - FAC1 - SUR1 - WAT1 - STR1$$

$$\dot{QAG} = OTAG - INAG$$

$$\dot{Q1} = FAC1 - FACL$$

$$\dot{Q2} = SUR1 - SURF$$

$$\dot{Q3} = WAT1 - WATR$$

$$\dot{Q4} = STR1 - STRM$$

$$\dot{CRES} = \quad - CUM$$

$$\dot{RR} = RR1 + RR2$$

$$\dot{ENSR} = ZSTR + SKLS$$

$$\dot{POP} = PTB$$

$$\dot{M1} = ROY2 + REV2 - INSK - INST$$

*a dot above the variable on the left hand side of the equation means rate of change with time.

Table 22

Description of Storages and Flows for Northern Great Plains Model

Quantity	Footnote*	Description	Reference
P(storage)	1	grassland gross production	NGPRP (1975).
FAC1(flow)	2	land rendered non-roductive due to mining facilities	Ballentine (1976).
FAC1(flow)	3	reclamation of facilities land	Ballentine (1976).
SUR1(flow)	4	land used for surface mining	Ballentine (1976).
SURF(flow)	5	reclamation rate of stripped land	Ballentine (1976).
WAT1(flow)	6	land affected by water table drawdown due to coal stripping	Ballentine (1976).
WATR(flow)	7	reclamation of land affected by water table drawdown	Ballentine (1976).
STR1(flow)	8	downstream land affected by mining	Ballentine (1976).
STRM(flow)	9	reclamation rate of downstream land	Ballentine (1976).
PAG(storage)	10	agricultural land	NGPRP (1975).

*Footnotes in Appendix V.

Table 22 (cont.)

QAG(storage)	11	productivity of agricultural land lost	Odum, E.P. (1971).
INAG(flow)	12	agricultural land disturbed from mining of coal	NGPRP (1975).
OTAG(flow)	13	reclamation rate of agricultural land	NGPRP (1975).
DEER(table function)	14	acreage of deer habitat lost	NGPRP (1975).
LOPE(table function)	15	acreage of antelope habitat lost	NGPRP (1975).
BG(table function)	16	acreage of big game habitat lost	NGPRP (1975).
CRES(storage)	17	tons of surface mineable coal in region	NGPRP (1975).
CUM(flow)	18	tons of coal mined	NGPRP (1975)
COSM(flow)	19	cost of mining	Ballentine (1976).
RR(storage)	20	total cumulative energy cost of train transportation	Section III-B.
RR1(flow)	21	natural productivity lost due to transport	Section III-B.
RR2	22	fixed costs, O and M and diesel fuel used in transport	Section III-B.

Table 22 (cont.)

POP(table function)	23	population influx due to development	NGPRP (1975).
ENSR(storage)	24	cumulative energy value of roads and schools to be constructed as a result of development	NGPRP (1975).
INSK(flow)	25	energy flow for construction of schools	NGPRP (1975).
SKLS(flow)	26	energy flow for construction of roads	NGPRP (1975).
M1(storage)	27	money storage for region	NGPRP (1975).
INST(flow)	28	flow of money out of region for roads	NGPRP (1975).
INSK(flow)	29	flow of money out of region for school construction	NGPRP (1975).
ROY2(flow)	30	money flow into region for coal royalties	NGPRP (1975).
REV2(flow)	31	money flow into region from coal revenues	NGPRP (1975).

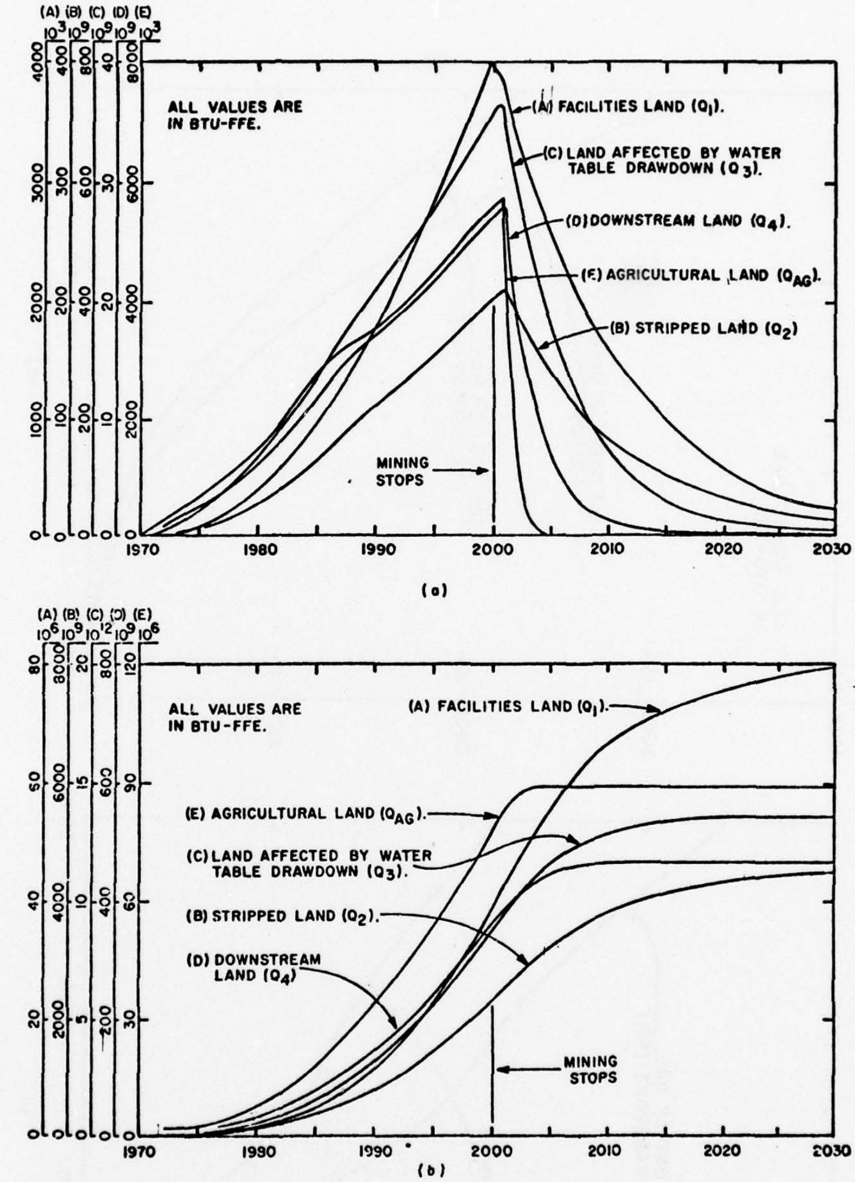


Figure 30. (a). Annual Gross Primary Productivity Losses Due to Land Occupied by Facilities, Land that is Stripped, Land Affected by Water Table Drawdown, Land Affected Downstream and Agricultural Land Mined, from 1970 to 2030.

(b). Cumulative Plots of the Above Curves for the Same 60 Year Period.

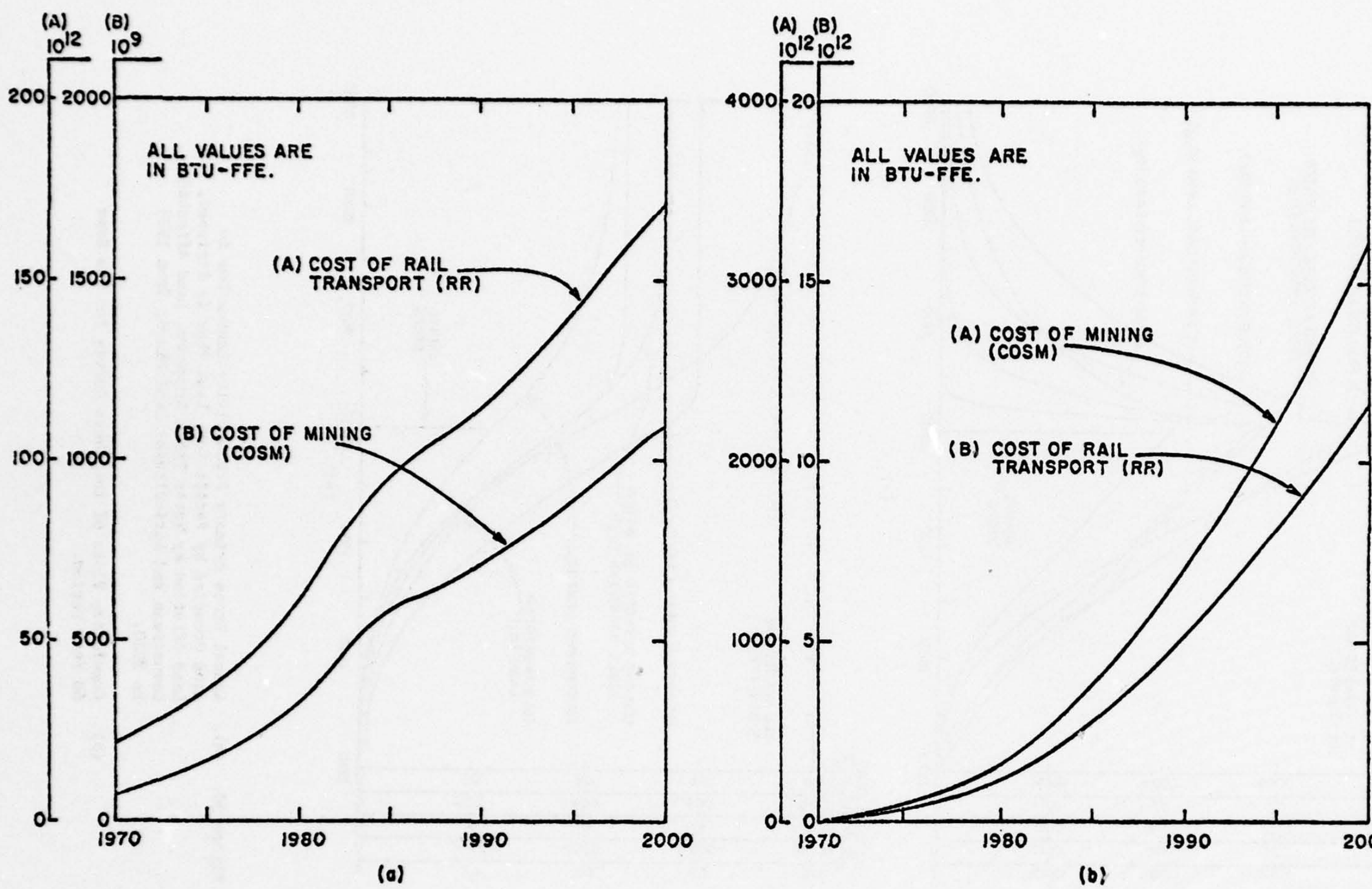


Figure 31. (a). Annual Energy Cost of Mining and Unit Train Transportation from 1970 to 2000.

(b). 30 Year Cumulative Energy Cost of Mining and Train Transport.

annual and cumulative energy cost of rail transport and mining. Figure 31b shows that the cost of transport (the lower curve but on a different scale) is over two orders of magnitude greater than the cost of mining. Figure 32 shows the energy cost of schools and roads. In Fig. 32b schools and roads have been combined into one curve.

The value for schools and roads gives some indication of the urban costs of development. Many urban effects are not considered, and in an accurate model these must be included. Reclamation costs also shown in Fig. 32 represent a value of $1500/acre for reclamation; however, this does not take into account the water which may be needed. During dry periods water may have to be diverted from other uses to irrigate reclaimed land. The energy value of this may be considerable.

In Fig. 33 the total energy costs are plotted against the energy delivered in coal. This is a dynamic, time varying net energy calculation. With a more detailed model the difference between total costs and total benefits could also be plotted. The minimum energy cost (including fuels and nature) could then be picked as the optimum combination of transport modes and tons mined. In the present simulation it was not necessary to do this since with the simple assumptions made in the model formuation, the curves in Fig. 33 merely rise linearly. It can be seen that the total energy delivered (the bottom curve) is much greater than the total energy costs in this simulation.

Another point of interest was the comparison of the money coming into the region with the money flowing out. Figure 34 indicates that the region will be receiving more money in revenues and royalties from coal than it will be spending on the two major expenditures considered (chools and roads). Again it should be mentioned that these results are not a realistic representation of the system. For instance, one major problem is whether the states will actually ever see the funds allocated to them. Another factor which was not even considered in his model is the socio-economic effects of a boom town in the region during the mining and after the mining has ceased in the year 2000.

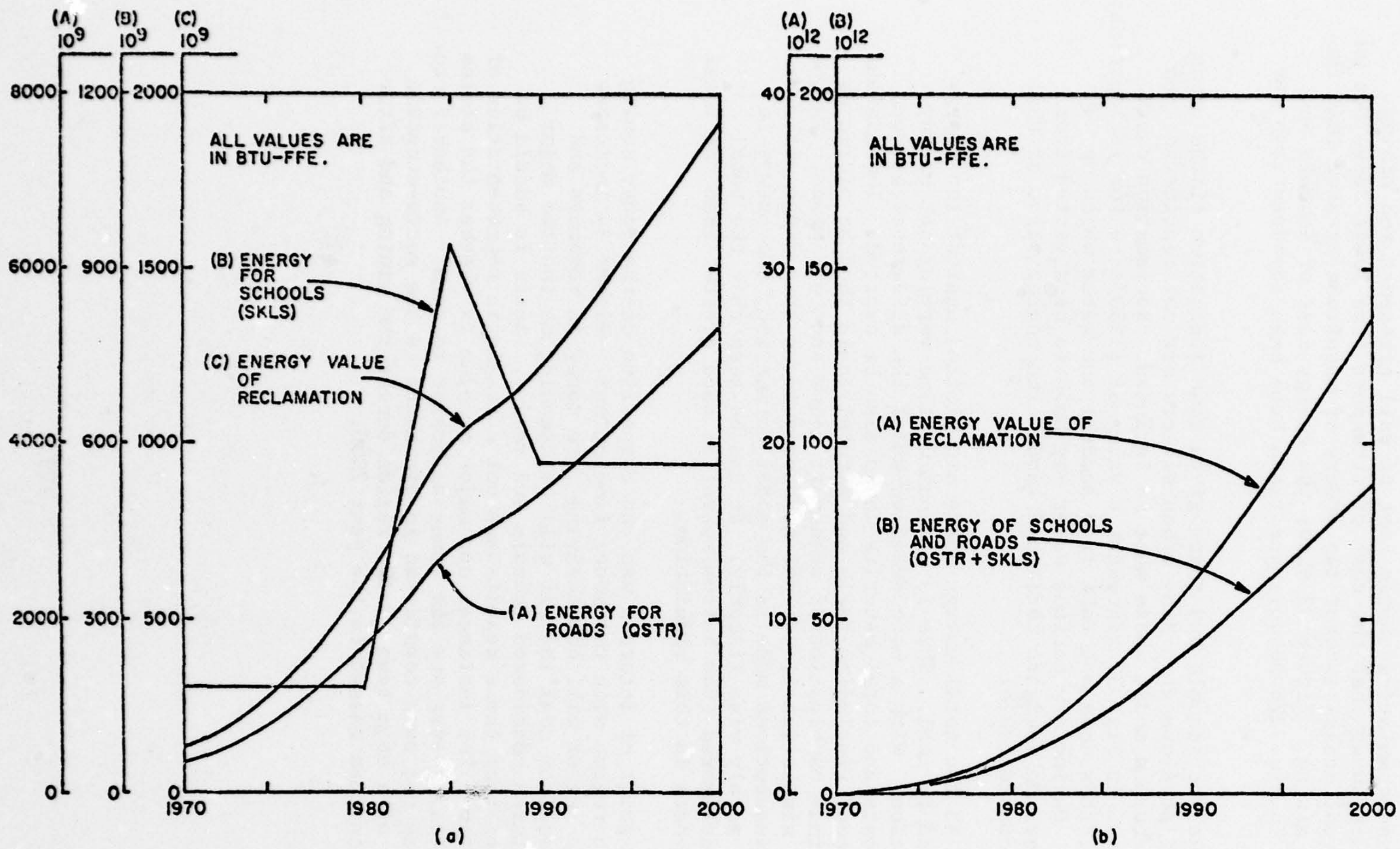
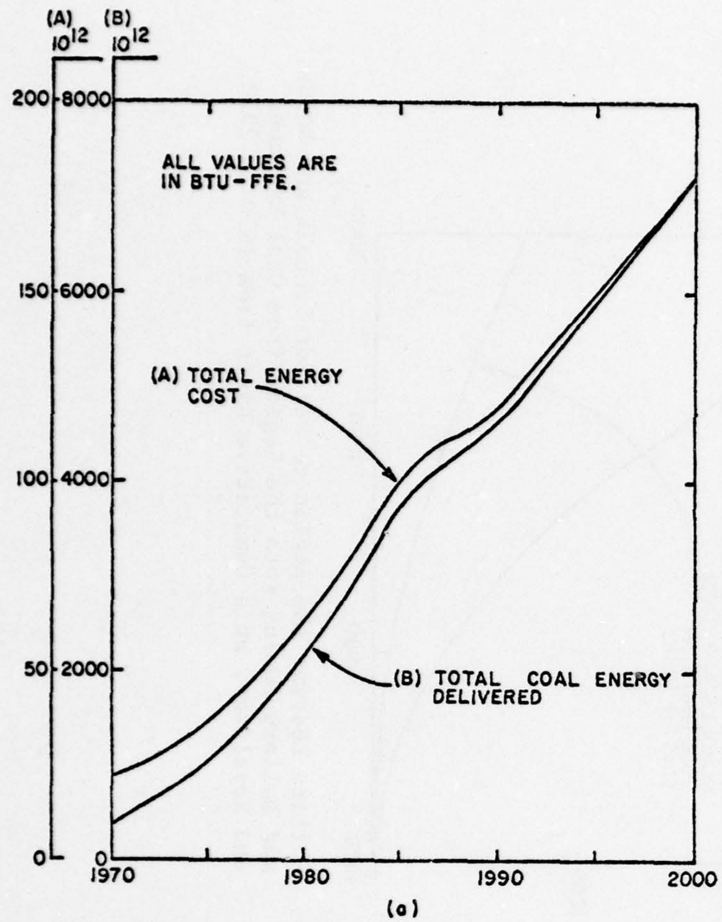


Figure 32. (a). Annual Energy Cost of Schools, Roads, and Reclamation of Disturbed Land from 1970 to 2000.

(b). Cumulative Energy Cost of Schools and Roads and Reclamation over 30 Year Period.



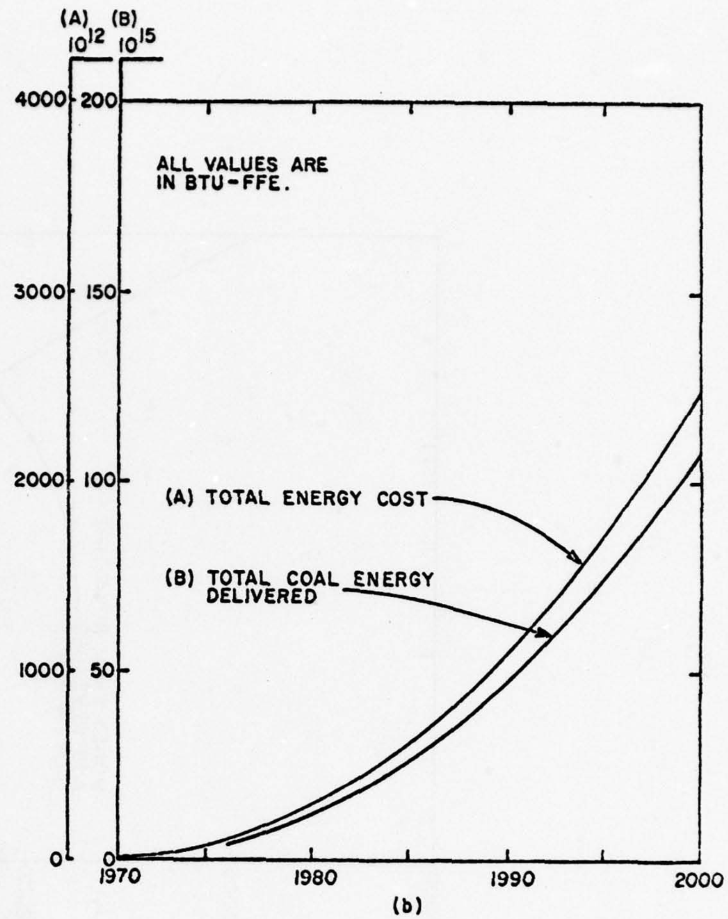


Figure 33. (a). Total Energy Cost (natural + mining + rail + schools + roads + reclamation) and Energy Value of the Coal Delivered on an Annual Basis from 1970 to 2000.

(b). Total Cost and Yield on a Cumulative Basis from 1970 to 2000.

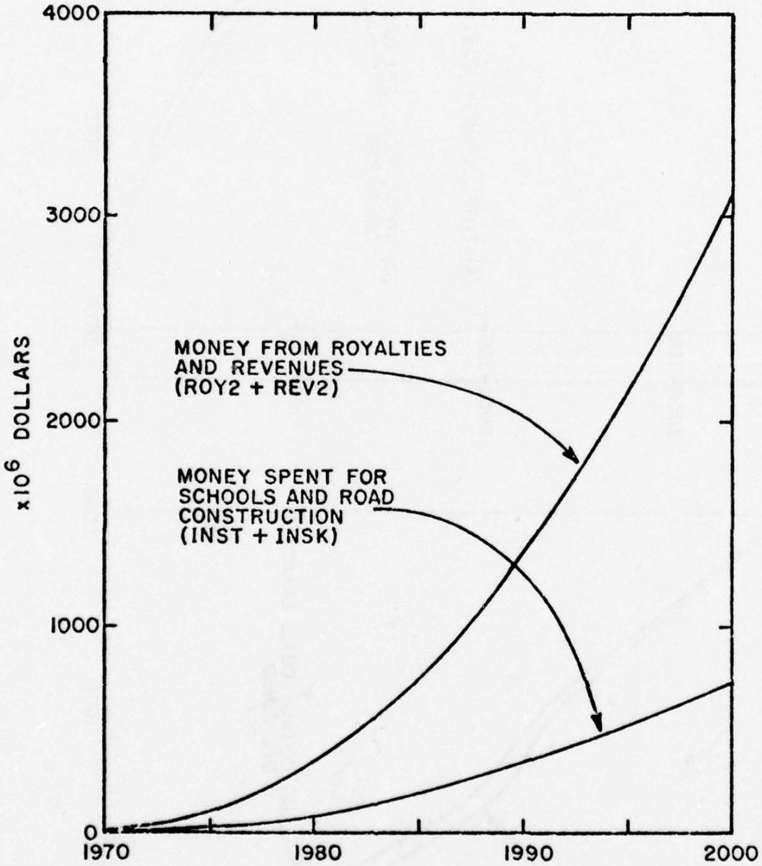


Figure 34. (a). Dollars Leaving the Region to Pay for Schools and Roads, and Dollars Coming into the Region from Coal Revenues and Royalites, on a Cumulative Basis from 1970 to 2000.

CHAPTER V
DISCUSSION

This report has presented a methodology which can be used for assessing the direct and indirect energetic effects of project and program developments. Theoretically, the flows of dollars and fuels in the system of man and the flows of energy in natural systems can be compared on an equal basis by converting all quantities to equivalent units of energy. This theory is in an early stage of development and requires considerable refinement. Energy theory enables an evaluation of all direct and indirect energy costs for fuels, capital, and labor for project construction and operation. It also allows the calculation of natural energy subsidies to a system and the natural energy costs associated with environmental destruction. As discussed in section II-B, energy analysis can be extended to a benefit/cost approach to assess energy benefits and costs. The concepts of energetics can also be applied on a regional scale in order to maximize the combined energy flows of man and nature in a given region. Accurate energetic analyses of transportation systems can be used to make decisions about transportation modes based on considerations of energy costs, both fossil fuel and natural. Aside from static calculations of energy flows, energy systems analysis is also amenable to describing systems and their interactions through mathematical models and performing simulation analysis to observe the dynamic response of these models.

Results

The results presented for energy costs and energy yield ratios of barges, railroads, pipelines and transmission lines were, in some cases, quite detailed. However, it is evident from sections III-A to III-D that many assumptions were required in order to complete the analyses. Due to the limited nature of this research project a great deal of reliance on economic flows and energy/dollar conversions were used to approximate energy flows. A larger research effort could be directed towards computation and understanding of only the energy flows in, and connected to, transportation systems of the economy. The models of transportation presented in sections III-A to III-D are examples of static analysis for the sole purpose of identifying major flows. To illustrate how energy systems analysis could be used for dynamic analysis, a computer simulation is presented in section IV on the Northern Great Plains. This section indicates how transportation could be included in a regional analysis and how multi-modal analysis could be modeled. This analysis could be extended from the considerations of one supply, one demand center with one commodity to multi-supply, demand, commodity situation. As presented in section III-E a comparison of direct and indirect energy costs between transport modes can be made for assessing energetic advantages.

Research Needs

The theory and methodology presented in this report could be better applied to transportation systems if the following research were conducted:

1. Research within each of the transportation industries to accurately assess the detailed energy and material flows associated with all phases of a transportation system.

2. Development of detailed energy models of the economy in order to assess the indirect energies associated with goods. This would avoid the use of economic data and approximate energy/dollar ratios.

3. The development of a theory for discounting energy, if necessary.

4. The use of data from the Corps of Engineers hydroelectric facilities and wave analysis to develop energy quality factors for potential and kinetic energy of water.

5. The study of a large number of energy transforming systems in order to calculate energy quality factors with greater precision.

6. Studies of the ecological parameters of riverine systems and other ecosystems adjacent to transport systems and the effects of transportation on these parameters.

7. As outlined in section II-A on spatial energy theory, national models of energy yield ratios for several energy regions in the country to determine energy yield ratios as a function of distance from an energy source. These sources could focus on the question if sources with higher yield ratios reflect greater economic competitiveness.

8. Development of models to show how and at what rate, transportation systems influence spatial development in adjoining regions.

9. In general, the study and evaluation of the local environmental effects of different transportation systems. In particular, a study of the effect of transport systems on the interaction of water and natural system production. For example, comparisons of the large scale efforts of pipelines versus railroads should be made. Increased river construction and control versus railroads should also be studied.

APPENDIX I

Energy Required for the Contruction of a Barge

In order to determine an approximate energy value or energy to dollar ratio for a barge, a calculation of the total energy necessary (from the raw materials to the finished product) was attempted. A barge is a fairly simple product in that it consists mostly of steel. Figure I-1 shows the main flows of energy, both direct and indirect, required for manufacture of the barge and production of the steel. Most of the major flows were quantified and are explained in the footnotes following Fig. I-1. The energy required for a typical covered hopper barge consists of the following (in units of 10^6 BTU's):

	Value (10^6 BTU)	Footnotes on Fig.
Steel Manufacture:		
Electrical Energy	926.6	16
	2501.6	17
	134	18
Natural gas	1590.4	16
Fuel oil	518.3	16
	51.8	19
Liquid petroleum	2.7	16
	0.27	20
Coal energy value	6632.	13
Coal mining and transport	370.	14
Iron ore mining and transport	61.8	15
Limestone mining	24.8	11
Lime mining	59.4	12
Barge Construction:		
Electrical	151.	2
	408.3	6
	22.8	7

Natural gas	100.	3
Fuel oil	43.6	4
	4.36	8
Gasoline	14.3	5
	1.43	9
Paint	28.75	10

TOTAL ENERGY = 13648.2×10^6 BTU

The dollar sale value of this barge was estimated at \$170,000 by the St. Louis Ship Co., half of which is attributable to goods. Therefore, the fossil fuel energy to dollar ratio for the goods is approximately:

$$\frac{13648.2 \times 10^6 \text{ BTU}}{\$85{,}000} = 160{,}567 \text{ BTU/Dollar}$$

If the natural energy to dollar ratio for 1974 is added on to this, the total work to produce a dollar of barge results. The approximate natural energy flow in the U.S. is 6.74×10^{15} kcal/yr = 26.82×10^{15} BTU/yr and the GNP for 1974 was approximately 1397.4×10^9, so that the Natural/GNP ratio was approximately:

$$\frac{\text{Natural Energy}}{\text{GNP}} \simeq 19{,}200 \text{ BTU/Dollar}$$

so that the total energy to dollar ratio for a barge was:

179767 BTU/Dollar

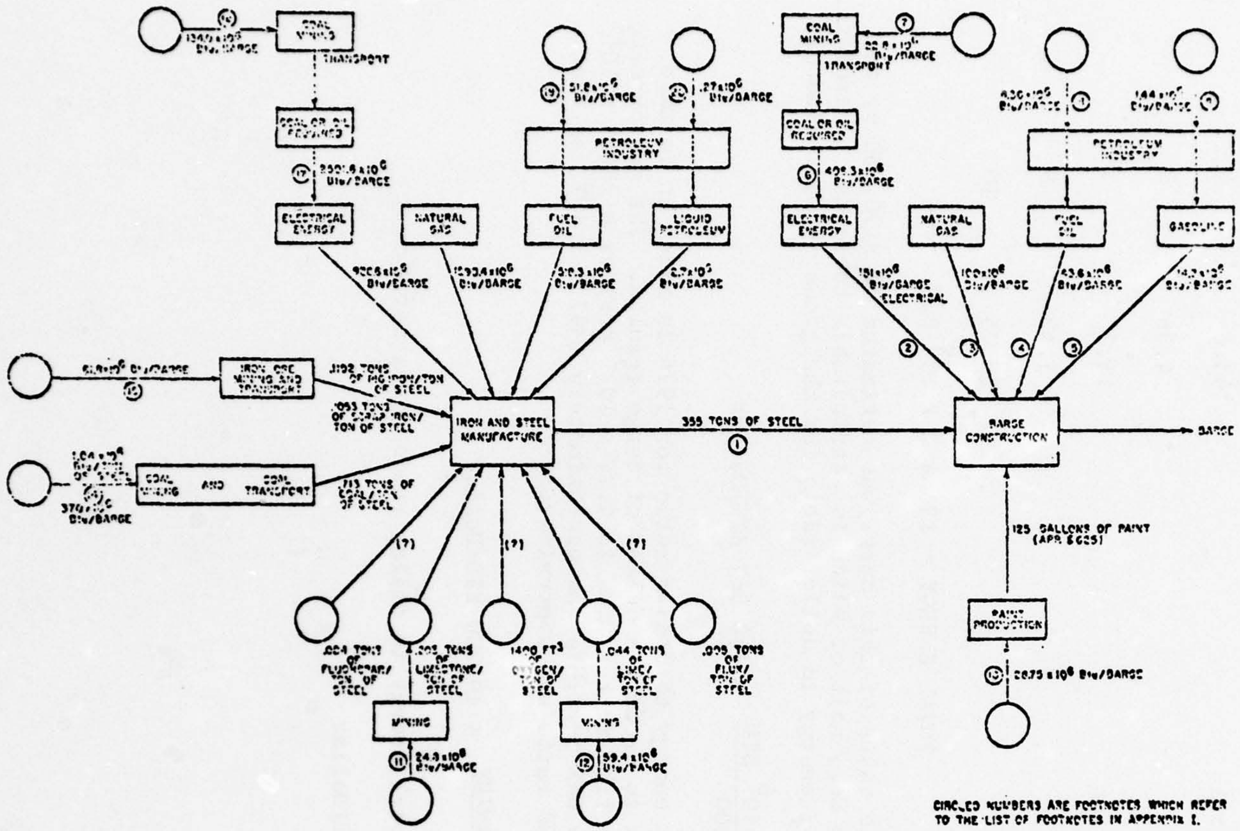


Figure I-1. Major Energy Flows Associated with the Construction of a 35' x 195' Barge.

Footnotes for Fig. I-1 Detailing the Calculations of the Energy Required for the Manufacture of a Barge

1. Amount of steel in a typical covered hopper barge (135' x 35') supplied by representatives of the St. Louis Ship Co. and approximated as 355 tons.

2. Approximately \$750 of electricity used in manufacture of barge (St. Louis Ship Co.). Assuming a 1975 price of electricity of \$0.017/kw-hr, then the amount of electricity used is:

$$\text{Electrical Energy} = \$750 \frac{\text{kw-hr}}{\$.017} = 44{,}118 \text{ kw-hr}$$
$$= 3.8 \times 10^7 \text{ kcal}$$
$$= 38 \times 10^6 \text{ kcal}$$
$$\text{Electrical Energy} = 151 \times 10^6 \text{ BTU/Barge}$$

3. Approximately \$100 of natural gas used in the manufacture of a barge (St. Louis Ship Co.). Natural gas used is approximately:

$$\text{Natural Gas Energy} = \$100 \frac{10^6 \text{BTU}}{\$1.0} = 100 \times 10^6 \text{ BTU/Barge}$$

4. Approximately \$100 of fuel oil is used in the manufacture of a barge (St. Louis Ship Co.). The energy of the fuel oil used is approximately:

$$\text{Fuel Oil Energy} = \$100 \cdot \frac{10^6 \text{BTU}}{\$2.294} = 43.6 \times 10^6 \text{ BTU/Barge}$$

5. Approximately \$50 of gasoline is used in the manufacture of a barge (St. Louis Ship Co.). The energy of the gasoline is then:

$$\text{Energy of Gasoline} = \$50 \frac{1 \text{ Gallon}}{\$0.5} \frac{3.6 \times 10^4 \text{ kcal}}{1 \text{ Gallon}} = 3.6 \times 10^6 \text{ kcal}$$

$$\text{Gasoline Energy } 14.3 \times 10^6 \text{ BTU/Barge}$$

6. It takes approximately 3.7 kcal of fossil fuel to generate 1 kcal of electricity (see Fig. 3c). Therefore, the fossil fuel required to generate 151×10^6 BTU of electricity is $3.7 \times 151 \times 10^6 = 559.3 \times 10^6$ BTU. Part of this energy is transformed to electrical energy so that the actual energy cost of the power plant is:

$$\text{Fossil Fuel Energy} = (559.3 - 151) \times 10^6 = 408.3 \times 10^6 \text{ BTU/Barge}$$

7. It takes approximately 1.46×10^6 BTU/Ton of coal for mining and delivery over 1000 miles by rail (Ballentine, 1976) so that the energy to mine and deliver the coal is approximately:

Footnotes to Figure I-1 (cont.)

$$\frac{1.46 \times 10^6 \text{ BTU}}{\text{Ton of Coal}} \times \frac{1 \text{ ton}}{26.2 \times 10^6 \text{ BTU}} \times (408.3 \times 10^6 \text{ BTU} =$$

$$22.8 \times 10^6 \text{ BTU/Barge}$$

8. It takes approximately 1 unit of energy to produce 10 units of petroleum product energy (Energy Consumption in Manufacturing, 1974) so that the energy required for fuel oil is approximately:

$$0.1 \times (43.6 \times 10^6 \text{ BTU}) = 4.36 \times 10^6 \text{ BTU/Barge}$$

9. Same as note 8 so that the energy to produce gasoline is approximately:

$$0.1 \times (14.3 \times 10^6 \text{ BTU}) = 14.3 \times 10^6 \text{ BTU/Barge}$$

10. One barge requires approximately 125 gallons of paint for an approximate value of \$625. The approximate energy/dollar ratio for resins is 46,000 BTU/\$ (Energy Consumption in Manufacturing, 1974) so that the energy required for paint is approximately:

$$\$625 \times 46000 \text{ BTU/\$} = 28.75 \times 10^6 \text{ BTU/Barge}$$

11. It takes approximately 0.344×10^6 BTU/ton to mine phosphate (Gilliland, 1973). This number was used to approximate limestone costs so that the energy of mining is approximately:

$$\text{Energy} = (0.203 \times 355) \text{ tons limestone/barge} \times 0.344 \times 10^6 \text{ BTU/ton}$$

$$\simeq 24.8 \times 10^6 \text{ BTU/Barge}$$

12. The energy cost of mining lime is approximately 3.8×10^6 BTU/ton. Thus;

$$\text{Energy/Barge} \simeq 0.044 \text{ tons lime/ton of steel} \times 355 \times 3.8 \times 10^6 \text{ BTU/ton}$$

$$\simeq 59.4 \times 10^6 \text{ BTU/Barge}$$

13. The energy of the coal used for steel manufacture is approximately:

$$0.713 \text{ tons} \times (355) \times 26.2 \times 10^6 \text{ BTU/ton of coal} \simeq$$

$$6632 \times 10^6 \text{ BTU/Barge}$$

Footnotes to Figure I-1 (cont.)

14. The amount of coal required for a barge is 0.713 tons of coal/ton of steel times 355 tons of steel which is 253.1 tons of coal. The energy cost of mining and transport is approximately 1.46×10^6 BTU/ton of coal (see note 7) so that the energy required is:

$$0.713 \frac{\text{tons of coal}}{\text{tons of steel}} \text{ X } 1.46 \times 10^6 \text{ BTU/ton of coal}$$

$$= 1.04 \times 10^6 \text{ BTU/ton of steel}$$

$$\text{or } 25.31 \frac{\text{tons of coal}}{\text{barge}} \text{ X } 1.46 \times 10^6 \text{ BTU/ton of coal}$$

$$\approx 370 \times 10^6 \text{ BTU/barge}$$

15. Assume that the cost of mining and transport is comparable to coal (see footnote 7) so that it takes 1.46×10^6 BTU/ton for mining and transport. Pig iron used per barge is 0.1192 x 355 tons = 42.3 tons. Energy cost of mining and transport is $42.3 \times 1.46 \times 10^6$ BTU/ton = 61.8×10^6 BTU/Barge. The Office of Science and Technology (Patterns of Energy Consumption in the U.S., Jan., 1972) gives the following numbers for steel production:

Electrical Energy	= 2.61×10^6 BTU/ton of steel
Natural Gas	= 4.48×10^6 BTU/ton of steel
Fuel Oil	= 1.46×10^6 BTU/ton of steel
Liquid Petroleum	= 0.0076×10^6 BTU/ton of steel

The above numbers multiplied by 355 tons of steel/barge gives the energy requirements per barge.

16. It takes 3.7 units of coal/unit of electrical energy. The coal energy expended is $(3.7 \times 926.6 - 926.6) \times 10^6$ BTU/Barge = 2501.6×10^6 BTU/Barge.

17. The energy cost of mining and transport (see note 7) is approximately 1.46×10^6 BTU/ton of coal so the energy required is:

$$\frac{1.46 \times 10^6 \text{ BTU}}{\text{ton of coal}} \; \frac{2501.6 \times 10^6 \text{ BTU of coal}}{\text{barge}} \; \frac{1 \text{ ton of coal}}{26.2 \times 10^6 \text{ BTU}}$$

$$= 139.4 \times 10^6 \text{ BTU/barge}$$

18. See note 8.

19. see note 9.

APPENDIX II

Energy Required for the Construction of a 5000 H.P. Towboat

Figure II-1 shows the main flows asscoiated with the construction of a towboat. The data was obtained from the St. Louis Ship Co. A towboat is not as simple as a barge in terms of material construction because of its main engines. Also, much of the data obtained was in terms of dollars rather than material quantities. Dollar flows were converted to their equivalent energy flows in the economy by using energy/dollar ratios for appropriate sectors of the economy (see Table II-1). The fossil fuel energy required for the construction of a typical 5000 H.P. towboat was calculated to be (see Fig. II-1):

	Value (10^6 BTU)	Footnote on Fig.
Miscellaneous (pipes, fittings, hydraulics)	20400	1
Steel	33000	2
Main Engines	26000	3
Electrical Energy	304	4
	790	8
	44	9
Natural Gas	200	5
Fuel Oil	87.2	6
	8.72	10
Gasoline	28.8	7
	2.88	11
TOTAL ENERGY	80866 x 10^6 BTU	

The approximate price of a towboat in 1975 was $\$2 \times 10^6$, approximately 51% of which went for materials. The approximate fossil fuel energy/dollar ratio for the towboats (excluding labor) is then:

$$\frac{80866 \times 10^6 \text{ BTU}}{0.51 \times (\$2 \times 10^6)} = 79280 \text{ BTU/\$}$$

Adding to this the natural energy/dollar ratio of 19200 BTU/Dollar for 1974 (see Appendix I and Table 3) gives a total energy/dollar ratio of:

$$(79280 + 19200) = 98480 \text{ BTU/\$}$$

Table II-1

Energy Coefficients for Specific I-0 Sectors for 1967 and 1974

Commodity and IO Sector	E_j(1967), BTU/\$[a]	E_j(1974), BTU/\$[b]
Pipe Industry (IO 4208)	74272	56713[c]
Steel Products (IO 3701)	267425	204203[d]
Motors, Generators (IO 5304)	62724	50267[e]

[a]Herendeen and Bullard, 1974

[b]This ratio is arrived at from the 1967 ratio by a formula which corrects for changing energy/dollar ratio and price ratios (see Table 15 and Section II A). The formula is:

$$E_j(1974) = E_j(1967) \times \frac{\text{Energy}(1974)/\text{GNP}(1974)}{\text{Energy}(1967)/\text{GNP}(1967)} \times \frac{\text{Price Index}(1967)}{\text{Price Index}(1974)}$$

where Energy = Total Energy Consumption

GNP = gross national product in constant dollars

Price Index = for individual economic sectors

[c] $E_j(1974) = 74272 \times \frac{126690}{126266} \times \frac{100}{131.4} = 56713$

[d] $E_j(1974) = 267425 \times \frac{126690}{126266} \times \frac{100}{131.4} = 204203$

[e] $E_j(1974) = 62724 \times \frac{126690}{126266} \times \frac{100}{125.2} = 50267$

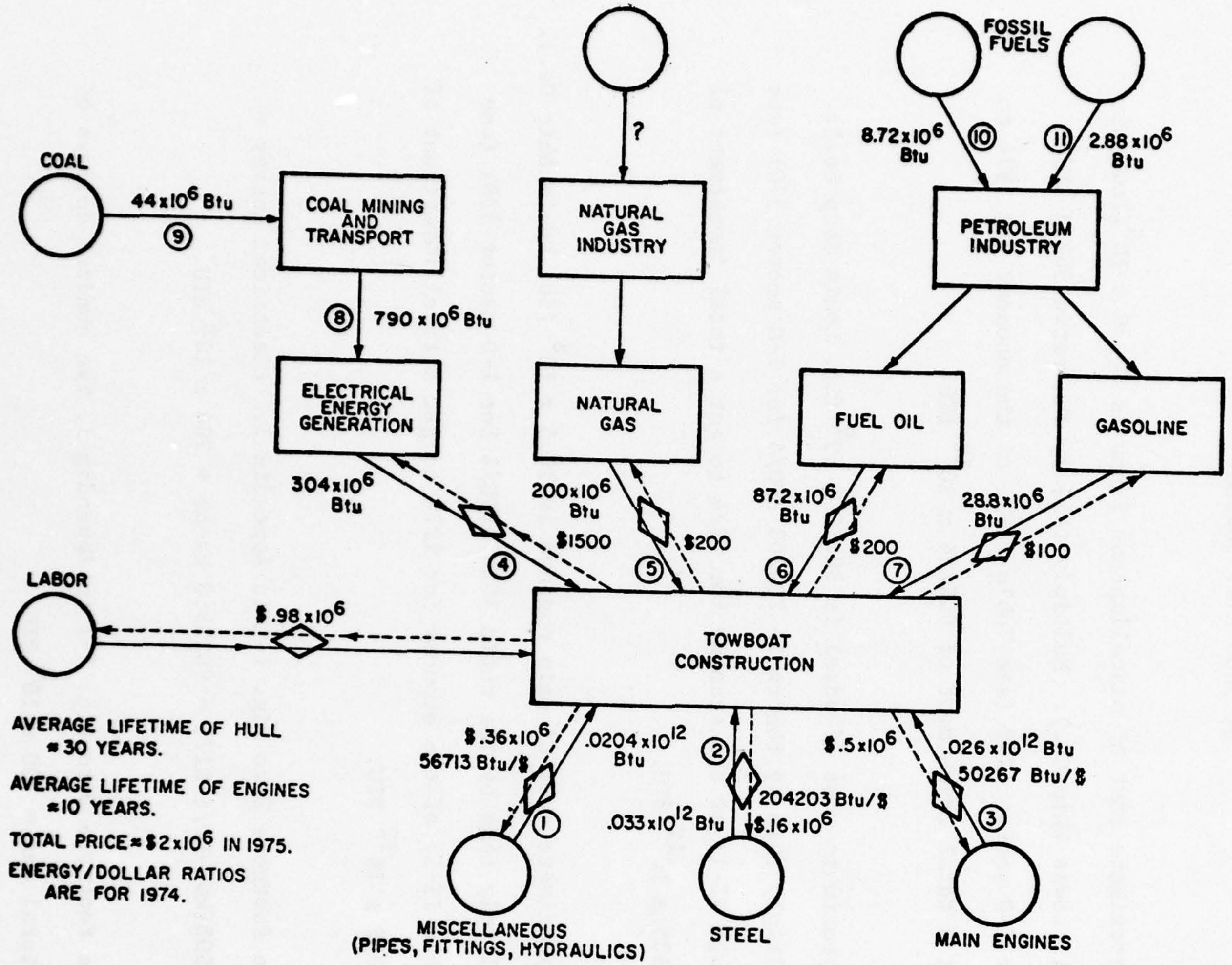


Figure II-1. Major Energy Flows Associated with the Construction of a 5000 H.P. Towboat.

Footnotes to Fig. II-1 Detailing Calculations for Energy Requirements of 5000 H.P. Towboat

1. Approximate cost of miscellaneous items is $\$0.36 \times 10^6$/Towboat (St. Louis Ship Co.). Multiply this by the ratio 56713 BTU/$ for I-0 sector 4208 (see Table II-1) of the economy for 1974 to get a total investment of 0.0204×10^{12} BTU.

2. Approximate cost of steel is $\$0.16 \times 10^6$ (St. Louis Ship Co.). Multiply this by the ratio 204203 BTU/$ for I-0 sector 3701 (see Table II-1) of the economy for 1974 to get a total investment of 0.033×10^{12} BTU.

3. Approximate cost of main engines is $\$0.5 \times 10^6$ (St. Louis Ship Co.). Multiply this by the ratio 50267 BTU/$ for I-0 sector 5304 (see Table II-1) of the economy for 1974 to get a total investment of 0.026×10^{12} BTU.

4. See footnote 2 to Fig. I-1 in Appendix I. Electrical Energy = \$1500(kw -hr/\$.017) = 88235.3 kw-hr = 304×10^6 BTU.

5. See footnote 3 to Fig. I-1 in Appendix I. Two hundred dollars of natural gas = 200×10^6 BTU.

Footnotes to Fig. II-1 (cont.)

6. See footnote 4 to Fig. I-1 in Appendix I. Two hundred dollars of fuel oil = 87.2×10^6 BTU.

7. See footnote 5 to Fig. I-1 in Appendix I. One hundred dollars of gasoline = 28.8×10^6 BTU.

8. See footnote 6 to Fig. I-1 in Appendix I. It takes approximately 3.6 BTU of fossil fuel to generate 1 BTU of electricity so that the fossil fuel required is $3.6 \times 304 \times 10^6$ BTU = 1094×10^6 BTU. Energy cost = $(1094 - 304) \times 10^6$ or 790 million BTU.

9. See footnote 7 to Fig. I-1 in Appendix I. Energy to mine and deliver 1000 miles is approximately

$$\frac{1.46 \times 10^6 \text{ BTU}}{\text{ton of coal}} \times \frac{1 \text{ ton}}{26.2 \text{ million BTU}} \times (790 \times 10^6 \text{ BTU}) = 44 \times 10^6 \text{ BTU}$$

10. See footnote 8 to Fig. I-1 in Appendix I. It takes approximately 1 unit of energy to produce 10 units of petroleum product.

$$0.1 \times 87.2 \times 10^6 \text{ BTU} = 8.72 \times 10^6 \text{ BTU}$$

11. See note 10.

$$0.1 \times 28.8 \times 10^6 \text{ BTU} = 2.88 \times 10^6 \text{ BTU}$$

APPENDIX III

Energy Required for the Proposed Construction of Locks and Dam #26.

The energy cost of Locks and Dam #26 was evaluated by estimating the various types of materials and activities by category from Supplement No. 1 to the General Design Memorandum for Locks and Dam #26 (replacement). The dollar costs were converted to energy costs by the appropriate energy/dollar conversion factor contained in Table III-1. The dollar costs and associated energy costs are listed in Table III-2 and diagrammed on Fig. III-1. As can be seen from Table III-2, the total energy of construction for Locks and Dam #26 would be 37.89×10^{12} BTU. Dividing this by the cost gives an energy/dollar ratio for this type of construction of

$$\frac{37.89 \times 10^{12} \text{ BTU}}{\$358 \times 10^{6}} = 105{,}838 \text{ BTU/\$}$$

Adding to this the natural ratio of 23290 BTU/$ for 1972 (see Table 3) gives a ratio of 129128 BTU/$.

Table III-1

Energy Coefficients for Specific I-0 Sectors for 1967 and 1972

Commodity & I-0 Sector	E_j(1967), BTU/\$[a]	E_j(1972), BTU/\$[b]
Concrete (IO 3612)	180661	148058[c]
Steel Products (IO 3701)	267425	230619[d]
New Construction, Highways (IO 1104)	117400	96214[e]
Clay and Stone Products (IO 3605 & 3615)	156409	130561[f]
New Construction, Other (IO 1105)	86662	71023[g]
New Construction, Non-residential (IO 1102)	67206	55078[h]
Maintenance Construction, Other (IO 1202)	57108	46802[i]
Cranes (IO 4603)	66328	62657[j]

[a]Herendeen and Bullard, 1974.

[b]See Table II-1, footnote b. The coefficient for 1972 can be found from

$$E_j(1972) = E_j(1967) \times \frac{\text{Energy}(1972)/\text{GNP}(1972)}{\text{Energy}(1967)/\text{GNP}(1967)} \times \frac{\text{Price Index}(1967)}{\text{Price Index}(1972)}$$

$$E_j(1972) = E_j(1967) \times \frac{125100 \text{ BTU/\$}}{126266 \text{ BTU/\$}} \times \frac{\text{Price Index}(1967)}{\text{Price Index}(1972)}$$

$$E_j(1972) = E_j(1967) \times 0.99 \times \frac{\text{Price Index}(1967)}{\text{Price Index}(1972)}$$

Price indexes obtained from Federal Reserve Bulletin: Industrial Production: S.A.

Footnotes to Table III-1 (cont.)

[c] $E_j(1972) = 180661 \times 0.99 \times \frac{100}{120.8} = 148{,}058$ BTU/$

(construction products index)

[d] $E_j(1972) = 267{,}425 \times 0.99 \times \frac{100}{114.8} = 230619$ BTU/$ (fabricated metal products index)

[e] $E_j(1972) = 117400 \times 0.99 \times \frac{100}{120.8} = 96214$ BTU/$

(construction products index)

[f] $E_j(1972) = 156049 \times 0.99 \times \frac{100}{118.6} = 130561$ BTU/$

(clay and stone products index)

[g] $E_j(1972) = 86662 \times 0.99 \times \frac{100}{120.8} = 71023$ BTU/$

(construction products index)

[h] $E_j(1972) = 67206 \times 0.99 \times \frac{100}{120.8} = 55078$ BTU/$

(construction products index)

[i] $E_j(1972) = 57108 \times 0.99 \times \frac{100}{120.8} = 46802$ BTU/$

(construction products index)

[j] $E_j(1972) = 66328 \times 0.99 \times \frac{100}{104.8} = 62657$ BTU/$

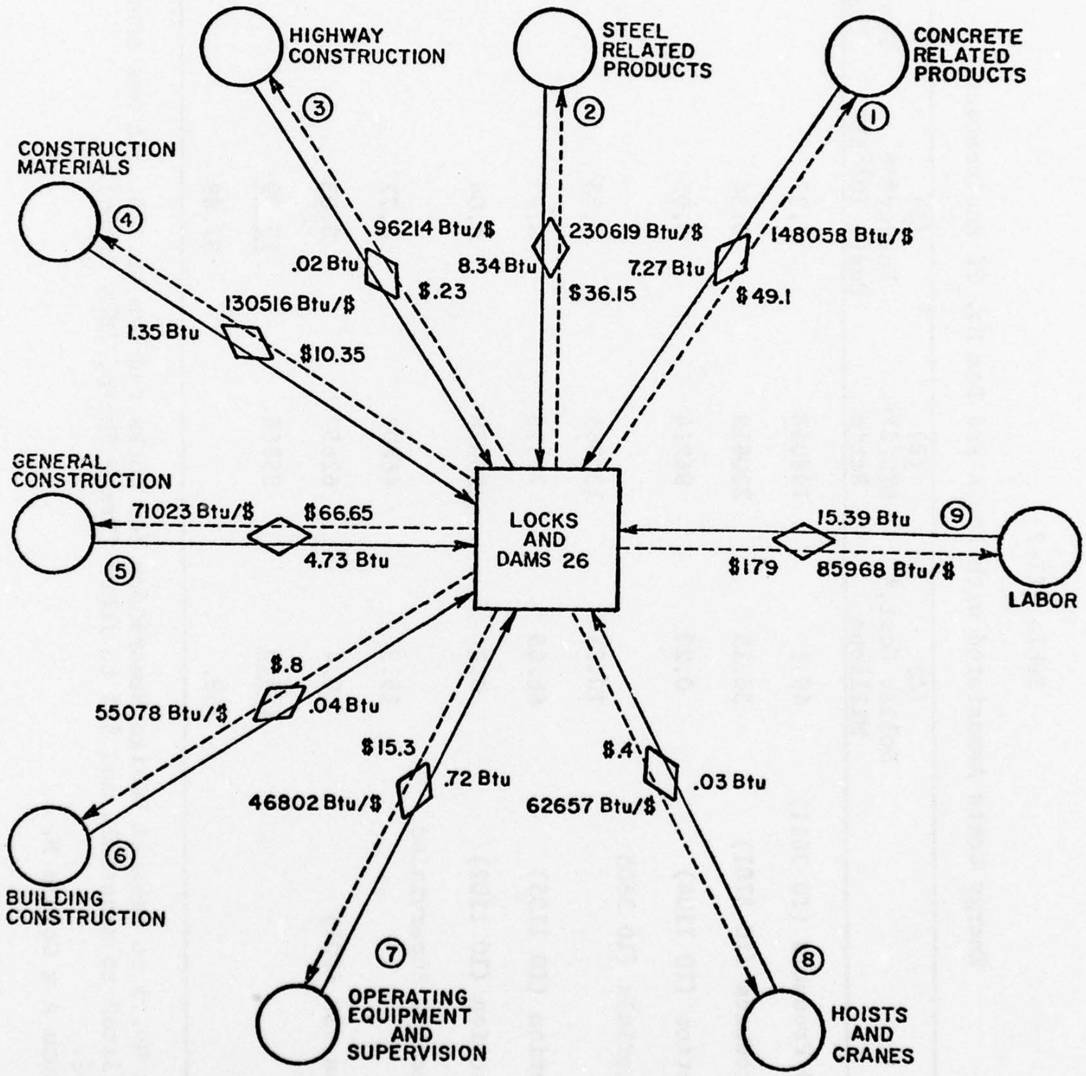
(building equipment index)

Table III-2

Energy Costs Associated with Locks and Dam No. 26 Replacement

Category	(A) Dollar Cost,* Millions	(B) BTU/$** Ratio	(C) Energy*** Cost, 10^{12}BTU	Footnote on Fig. III-1
Concrete Related Products (IO 3611)	49.1	148058	7.27	1
Steel Related Products (IO 3701)	36.15	230619	8.34	2
Highway Construction (IO 1104)	0.23	96214	0.02	3
Construction Materials (IO 3605 & 3615)	10.35	130561	1.35	4
General Construction (IO 1105)	66.65	71023	4.73	5
Building Construction (IO 1102)	0.8	55078	0.04	6
Operating Equipment & Supervision (IO 1202)	15.3	46802	0.72	7
Hoists and Cranes (IO 4603)	0.4	62657	0.03	8
Labor	179.0	85968	15.39	9
TOTALS	358.		37.89	

*See Supplement No. 1 to General Design Memorandum for Locks and Dam No. 26. It was assumed that 50% of cost related to materials and 50% to labor (Frank Sharp, INSA Group).
**See Table III-1.
***Column C = Column A x Column B.



ALL ENERGY FLOWS ARE IN UNITS OF 10^{12} Btu's. (————→)

ALL DOLLAR FLOWS ARE IN MILLIONS OF DOLLARS. (- - - - - - →)

CIRCLED NUMBERS REFER TO FOOTNOTES ON TABLE III-2.

Figure III-1. Major Energy Flows for the Proposed Replacement of Locks and Dam No. 26.

APPENDIX IV

Footnotes to Table 12 in Section III-C

Footnotes to Table 12

CAPITAL INVESTMENTS

b. Slurry preparation plant and well construction

Total Cost $\$50 \times 10^6$ (Rieber, 1975)

Annual Cost (35 yr lifetime) $\$1.43 \times 10^6$/yr

assume 2/3 of cost associated with preparation equipment + construction and 1/3 of cost associated with well preparation

Slurry preparation equipment + construction

$(2/3) \times (\$1.43 \times 10^6/\text{yr}) = \$953,333/\text{yr}$

Well preparation

$(1/3) \times (\$1.43 \times 10^6/\text{yr}) = \underline{\$476,666/\text{yr}}$

Total $1,429,999/yr

Detailed breakdown of economic costs in order to use industrial sector energy/dollar ratios.

Slurry preparation equipment + construction

	estimated % of total cost	%/yr
Equipment	70	(0.7)(953,333) = 667,333
Construction	20	(.20)(953,333) = 190,666
Indirect Costs	10	(.10)(953,333) = 95,333

IO Sector	BTU/$	% Tot.	$/yr	10^{10}BTU/yr
Steel Products (3701)	267,425	40	684,000	18.29
New Const. Pub. Ut. (1103)	79,610	35	598,500	4.76
Pumps, Compressors (4901)	55,256	10	171,000	0.94
Motors, Generators (5304)	62,724	10	171,000	1.07
Communications (6600)	3,470	1	17,100	0.005
Personal Service (7202)	43,723	4	68,400	0.30
Total for Pipeline and Pump Stations			1,710,000	25.37

d. Dewatering Facilities

Total Cost $\quad$ \$40 x 10^6 *(Rieber, 1975)*

Annual Cost (35 yr lifetime) $\quad$ \$1.14 x 10^6/yr

IO Sector	BTU/$	% Tot.	$/yr	10^{10}BTU/yr
Steel Products (3701)	267,425	30	342,000	9.15
New Const. Pub. Ut. (1103)	79,610	35	399,000	3.18
Motors, Generators (5304)	62,724	8	91,200	0.50
Pumps, Compressors (4907)	55,256	8	91,200	0.50
Gen. Indust. Mach. (4907)	69,610	10	114,000	0.79
Conveyors (4602)	69,576	1	11,400	0.08
Concrete (3612)	163,407	2	22,800	0.37

Footnotes to Table 12 (cont.)

(The following column headings refer to all sections below)

IO Sector	A Energy coeff.[aa] BTU/$(1974)	Estimated % of total	B $/yr[bb]	C 10^{10} BTU/yr[cc]
Detailed breakdown of Equipment + Machinery ($667,333)				
Fab. Struct. Steel (4004)	114,345	20	133,466	1.53
Conveyors (4602)	69,576	5	33,366	0.23
Indus. Truck (4604)	71,645	5	33,366	0.24
Pumps, Compressors (4901)	63,467	20	133,466	0.85
Motors, Generators (5304)	69,449	25	166,833	1.16
Steel Products (3701)	223,330	25	166,833	3.73
Subtotal 1			667,333	7.74

aa See Table IV-1 for Input-Output BTU/$ coefficients

bb Column B is percent times $667,330 for equipment + machinery costs

cc Column C is Column A x Column B

IO Sector	A Energy coeff. BTU/$(1974)	Estimated % of total	B $/yr	C 10^{10} BTU/yr
Detailed Breakdown of Construction Cost ($190,666/yr)				
New Const. Pub. Ut. (1103)	84,088	100	190,666	1.60
Subtotal 2			190,666	1.60

Footnotes to Table 12 (cont.)

Indirect Costs ($95,333/yr)

Personal Service (7202)	55,745	100	95,333	0.53
Subtotal 3			95,333	0.53

Detailed Breakdown for Well Preparation + Equipment (476,666 $/yr

New Const. Pub. Ut. (1103)	84,088	20	95,333	0.80
Steel Prod. (3701)	223,330	10	47,666	1.06
Pumps, Compressors (4901)	63,467	30	142,999	0.91
Motors, Generators (5304)	69,449	30	142,999	0.99
Personal Service (7202)	55,745	10	47,666	0.27
Subtotal 4			476,666	4.03
Total for Slurry, Preparation + Wells (Subtotals 1 + 2 + 3 + 4)			1,429,999	13.09

c. PIPELINE AND PUMP STATIONS

Total Cost $60 x 10^6 (Rieber, 1975)

Annual Cost (35 yr lifetime) $1.71 x 10^6/yr

Indust. Furnace (4906)	75,223	5	57,000	0.43
Total for Dewatering Facilities			1,140,000	15.07

GOODS AND SERVICES

e. Slurry Preparation Plant And Wells

($\$500,000/yr) \times (65,745\ BTU/\$) = 3.29 \times 10^{10}$ BTU/yr

Rieber, 1975) IO Sector 1202

f. Pipeline and Pumpstations

($\$500,000/yr) \times (65,745\ BTU/\$) = 3.29 \times 10^{10}$ BTU/yr

(Rieber, 1975) IO Sector 1202

g. Dewatering Facilities

($\$5,550,000/yr) \times (65,747\ BTU/\$) = 36.49 \times 10^{10}$ BTU/yr

(Dina, 1974) IO Maintenance

($\$1,156,000/yr) \times (202,484\ BTU/\$) = 23.41 \times 10^{10}$ BTU/yr

(Dina, 1974) IO Chemicals

Total 59.90×10^{10} BTU/yr

LABOR

Direct labor for slurry pipeline process	$\$10^6$/yr
82 persons @ $19,512/yr	1.6 (Rieber, 1975)
Administrative Costs	0.8
Total	2.4

h. Slurry preparation plant

Assume that each part of the process is responsible for 1/3 of the total administrative cost and the direct labor is proportional to

Footnotes to Table 12 (cont.)

the number of employees in each sector

$[(\$0.8 \times 10^6/yr + 3) + (44 \text{ persons} \times \$19{,}512/yr)] \times (18{,}700 \frac{kcal}{\$} \times$

$3.96 \text{ BTU/kcal}) = 8.33 \times 10^{10} \text{ BTU/yr}$

i. Pipeline and Pumpstations

$[(\$0.8 \times 10^6/yr \div 3) + (8 \text{ persons} \times \$19{,}512/yr)] \times (18{,}700 \frac{kcal}{\$} \times$

$3.96 \text{ BTU/kcal}) = 8.33 \times 10^{10} \text{ BTU/yr}$

j. Dewatering Facilities

$[(\$0.8 \times 10^6/yr) \div 3) + (32 \text{ persons} \times \$19{,}512/yr)] \times (18{,}700 \frac{kcal}{\$} \times$

$3.96 \text{ BTU/kcal}) = 6.60 \times 10^{10} \text{ BTU/yr}$

DIRECT USE OF FOSSIL FUELS

Slurry preparation plant and pump stations use 260 BTU/ton/mile/yr of fossil fuel energy (Montfort, personal communication). Assume that of the total 260 BTU's, 208 BTU's are coal and 52 BTU's are electricity. Also assume that this direct use of fuel is evenly divided between the preparation plant and pump stations.

k. Slurry preparation plant

$([(208 \text{ BTU/ton mile}) + (52 \text{ BTU elec./ton mile} \times 3.7 \frac{\text{BTU coal}}{\text{BTE elec}})] \div 2 \times$

$(5 \times 10^6 \text{ tons} \times 273 \text{ miles}) = 27.33 \times 10^{10} \text{ BTU/yr}$

l. Pipeline and Pumpstations

same as k. above $= 27.33 \times 10^{10}$ BTU/yr

m. Assume that the dewatering facilities utilize the same amount of fossil fuels as the slurry plant and pumpstations $= 27.33 \times 10^{10}$ BTU/yr

WATER COST

n. $(\$500{,}000/yr) \times (198{,}321 \text{ BTU/\$}) = 9.91 \times 10^{10} \text{ BTU/yr}$

(Rieber, 1975) Water Transport

IO Sector 6504

Table IV-1

Energy Coefficient for Specific IO Sectors for 1974[a]

Commodity + IO Sector	E_j 1967[b]	E_j BTU/$	E_j^T BTU/$[c]
Fab. Struct. Steel (4004)	124,602	95,145	114,345[d]
Aluminum (IO 3808)	244,677	186,833	206,033[e]
Concrete (IO 3612)	180,661	144,207	163,407[f]
New Const. Pub. Ut. (IO 1103)	79,610	64,888	84,088[g]
Maint. Const. (IO 1202)	57,108	46,547	65,747[h]
Steel Prod. (IO 3701)	267,425	204,130	223,330[i]
Const. Mach. (IO 4501)	68,040	53,274	72,474[j]
Conveyors (IO 4602)	64,339	50,376	69,576[k]
Indust. Truck (IO 4604)	59,190	52,444	71,645[l]
Pumps, Compressors (IO 4901)	55,256	44,267	63,467[m]
Indus. Furnaces (IO 4906)	71,552	53,637	72,837[n]
Motors + Generators (IO 5304)	62,724	50,249	69,449[o]
Water Transport (IO 6504)	223,589	179,121	198,321[p]
Communications (IO 6600)	3,470	2,689	21,889[q]
Personal Service (IO 7202)	43,723	36,545	55,745[r]
Inorganic-Organic Chem. (IO 2701)	281,962	183,284	202,484[s]
Industrial Furnace (IO 4906)	71,552	56,023	75,223[t]
Gen. Indus. Machinery (IO 4907)	64,383	50,410	69,610[u]

Footnotes to Table IV-1

[a]Herendeen + Bullard, 1974

[b]This includes only the fossil fuels used in economy.

[c]This ratio includes both fossil fuel and natural energy work in economy. See Table 15.

The ratio of natural energy to GNP for 1974 was 19,200 BTU/$ = E^N

$$E_j^T(1974) = E_j(1974) + E^N(1974)$$

$$E_j(1974) = E_j(1967) \times \frac{\text{Total Energy(1974)in BTU}}{\text{Total Energy(1967)in BTU}} \times \frac{\text{GNP(1967)}}{\text{GNP(1974)}} \times \frac{\text{Price Index(1967)}}{\text{Price Index(1974)}}$$

Where E_j = Energy Coefficient in BTU/$

Total Energy in BTU = Total Energy input into U.S. Economy

GNP = Gross National Product of U.S. Economy in constant dollars

Price Index = price index for each IO Sector

Can also be written:

$$E_j(1974) = E_j(1967) \times \frac{\text{Energy(1974)/GNP(1974)}}{\text{Energy(1967)/GNP(1967)}} \times \frac{\text{Price Index(1967)}}{\text{Price Index(1974)}}$$

$$E_j^T(1974) = E_j(1974) + E^N$$

where E^N = Natural Energy input in 1974

[d]$E_j^T(1974) = (124{,}602\ \text{BTU/\$}) \times (\frac{126{,}690}{126{,}266}\text{BTU/\$}) \times (\frac{100.0}{131.4}) + 19{,}200\frac{\text{BTU}}{\$} = 114{,}345\ \frac{\text{BTU}}{\$}$

[e]$E_j^T(1974) - (244{,}677\frac{\text{BTU}}{\$}) \times (\frac{126{,}690}{126{,}266}\ \frac{\text{BTU}}{\$}) \times (\frac{100.0}{131.4}) + 19{,}200\frac{\text{BTU}}{\$} = 206{,}033\ \frac{\text{BTU}}{\$}$

[f]$E_j\,T(1974) = (244{,}677\frac{\text{BTU}}{\$}) \times (\frac{126{,}690}{126{,}266}\ \frac{\text{BTU}}{\$}) \times (\frac{100.0}{125.7}) + 19{,}200\frac{\text{BTU}}{\$} = 206{,}033\ \frac{\text{BTU}}{\$}$

Footnotes to Table IV-1 (cont.)

$$^{g}E_j^{T}(1974) = (79{,}610\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{123.1})+19{,}200\frac{BTU}{\$} = 84{,}088\ \frac{BTU}{\$}$$

$$^{h}E_j^{T}(1974) = (57{,}108\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{123.1})+19{,}200\frac{BTU}{\$} = 65{,}747\ \frac{BTU}{\$}$$

$$^{i}E_j^{T}(1974) = (267{,}425\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{131.4})+19{,}200\frac{BTU}{\$} = 223{,}330\ \frac{BTU}{\$}$$

$$^{j}E_j^{T}(1974) = (68{,}040\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{128.1})+19{,}200\frac{BTU}{\$} = 72{,}474\ \frac{BTU}{\$}$$

$$^{k}E_j^{T}(1974) = (64{,}339\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{128.1})+19{,}200\frac{BTU}{\$} = 69{,}576\ \frac{BTU}{\$}$$

$$^{l}E_j^{T}(1974) = (59{,}190\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{113.2})+19{,}200\frac{BTU}{\$} = 71{,}645\ \frac{BTU}{\$}$$

$$^{m}E_j^{T}(1974) = (55{,}256\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{125.2})+19{,}200\frac{BTU}{\$} = 63{,}467\ \frac{BTU}{\$}$$

$$^{n}E_j^{T}(1974) = (71{,}552\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{125.2})+19{,}200\frac{BTU}{\$} = 72{,}837\ \frac{BTU}{\$}$$

$$^{o}E_j^{T}(1974) = (62{,}724\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{125.2})+19{,}200\frac{BTU}{\$} = 69{,}449\ \frac{BTU}{\$}$$

$$^{p}E_j^{T}(1974) = (223{,}589\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{125.2})+19{,}200\frac{BTU}{\$} = 198{,}321\ \frac{BTU}{\$}$$

$$^{q}E_j^{T}(1974) = (3{,}740\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{129.4})+19{,}200\frac{BTU}{\$} = 21{,}889\ \frac{BTU}{\$}$$

$$^{r}E_j^{T}(1974) = (44{,}723\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{120.0})+19{,}200\frac{BTU}{\$} = 55{,}745\ \frac{BTU}{\$}$$

$$^{s}E_j^{T}(1974) = (281{,}962\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{154.3})+19{,}200\frac{BTU}{\$} = 202{,}484\ \frac{BTU}{\$}$$

$$^{t}E_j^{T}(1974) = (71{,}552\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{128.1})+19{,}200\frac{BTU}{\$} = 75{,}223\ \frac{BTU}{\$}$$

$$^{u}E_j^{T}(1974) = (64{,}383\frac{BTU}{\$})\times(\frac{126{,}690}{126{,}266}\ \frac{BTU}{\$})\times(\frac{100.0}{128.1})+19{,}200\frac{BTU}{\$} = 69{,}610\frac{BTU}{\$}$$

APPENDIX V

Footnotes to Table 22 and DYNAMO Computer Program for the Northern Great Plains Simulation Model

Footnotes to Table 22

1. Gross Primary Productivity for <u>Sporobolus</u> communities was assumed to be 800 $gm/m^2/yr$. This was then converted to BTU by the computer program in the following manner: 1 gm primary production equals 4.5 kcal of sugar equivalent energy. It requires 20 units of sugar equivalent to equal 1 unit of fossil fuel equivalent energy.
2. Cumulative coal production by year 2000 is 650×10^6 tons. Total mine and plant facilities were $7.5 \times 10^{-4}\%$ of this amount. This flow is also on a cumulative basis. Since the ratio of mined land to facilities land did not change for the 3 coal development plans (p. 56, NGPRP), 7.5×10^{-6} acres/ton of coal mined was programmed into model.
3. This rate begins in the year 2000 and from that point on the rate is K_1Q1. The coefficient K is 0.1 since it requires ≈ 50 years to reestablish a climax community $5\tau = 50$

$$\tau = 10$$

$$K_1 = \frac{1}{\tau} = 0.1$$

τ = time constant

4. This flow is based on 35 acres of land stripped for every 10^6 tons of coal mined. 80% of the total is assumed to be grassland.
5. Reclamation rate is K_2Q2. K_2 is calculated as in Note 3.

Footnotes to Table 22 (cont.)

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6. 8.2 acres is assumed affected for each acre mined. The effect is taken as 50% of gross production.

7. Reclamation rate is K_3Q3. Land is restored to normal productivity in 30 years. $5\tau = 30$

$$\tau = 6$$

$$K_3 = \frac{1}{\tau} = 0.17$$

8. 0.9 acres downstream is affected for each acre mined. The effect is taken to be 30% loss in productivity per acre.

9. Reclamation of land in this category is 15 years, the rate is K_4Q4.

$$5\tau = 15$$

$$t = 3$$

$$K_4 = 0.33$$

10. 694,000 acres of land is under irrigation.

11. Gross Primary Productivity of subsidized agricultural land is 12000 $kcal/m^2/yr$.

12. 19% of land stripped is agricultural land.

13. Land is reclaimed for agricultural use after 5 years, rate is $QAG \times K_{AG}$ $\quad K_{AG} = 5\tau = 5$

$$\tau = 1$$

$$K_{AG} = 1$$

Footnotes to Table 22 (cont.)

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14. Deer habitat lost is not actually part of the dynamic program since no research has been done to determine what migration or loss of wildlife will occur in the event of mining. This is included in the model for demonstration purposes as a table function.

15. See Note 13.

16. See Note 14.

17. 80.2 billion tons of coal are at depths amenable to surface mining.

18. The coal development plans used were explained earlier in this section.

19. The natural cost of mining was calcualted in Q1 of the model. For the other costs of mining the variable costs of general support, fuel, and electric power were calculated to be 278×10^{10} BTU/ 9.2×10^{6} tons of coal mined.

20. This is a cumulative total of the total cost of RR transportation.

21. Natural system loss is 1.8×10^{10} BTU.

22. Fixed cost is determined by multiplying the fixed cost of one unit train calculated in Section III-B $\frac{1.69 \times 10^{10} \text{ BTU}}{500{,}000 \text{ tons}}$ then multiplying, not by the cumulative tons shipped, but the largest annual number of tons hauled. For CDP II this would be 362×10^{6} tons. To this is added the variable costs 22.1×10^{10} BTU/ 500,000 tons.

Footnotes to Table 22 (cont.)

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23. This is a table function determined by projections of the NGPRP.

24. The cumulative energy cost of roads and schools.

25. Dollar estimates for these costs were converted to energy values by multiplying by 9.3×10^4 BTU/\$. IO sector 1102 (Herendeen and Bullard, 1974) was updated to 1974 value = 7.4×10^4 BTU/\$, as done in Table 15.

    $(7.4 \times 10^4 + 19200 \text{ BTU/\$}) = 9.3 \times 10^4 \text{ BTU/\$}$

26. IO sector 1104 = $11.3 \times 10^4 \text{ BTU/\$} + \dfrac{19{,}200 \text{ BTU}}{\$} = 132{,}601 \text{ BTU/\$}$

27. This is the dollar storage of the region. It is a measure of the net gain or loss of money due to coal development.

28. The dollar value of road construction was calculated to be 0.11 x tons mined/year.

29. This is a table function based on data in NGPRP, p. 130.

30. Royalties from coal into the region is \$0.43/ton coal mined.

31. Tax revenues from coal are \$0.16/ton mined.

```
* NGP MODEL
L P.K=P.J+DT*(-FAC1.JK-SUR1.JK-WAT1.JK-STR1.JK+FACL.JK+
X   SURF.JK+WATR.JK+STRM.JK)
L Q1.K=Q1.J+DT*(FAC1.JK-FACL.JK)
L Q2.K=Q2.J+DT*(SUR1.JK-SURF.JK)
L Q3.K=Q3.J+DT*(WAT1.JK-WATR.JK)
L Q4.K=Q4.J+DT*(STR1.JK-STRM.JK)
R FAC1.KL=AUX1.K
A AUX1.K=7.5E-6*AUX5.K*AUX4.K
R FACL.KL=AUX2.K
A AUX2.K=FIFGE(AUX3.K,0,TIME.K,30)
A AUX3.K=CON2*Q1.K
C CON2=.1
R SUR1.KL=SU4.K
A AUX4.K=35E-6*4057*500*4.5*3.95*.05
A AUX5.K=FIFGE(0,AUX6.K,TIME.K,31)
A AUX6.K=TABLE(TAB6,TIME.K,0,30,5)
T TAB6=21.3E6/52E6/107E6/192E6/230E6/295E6/362E6
R SURF.KL=Q2.K*CON2
R WAT1.KL=AUX4.K*AUX5.K*CON3*.5
C CON3=8.2
R WATR.KL=Q3.K*CON4
C CON4=.17
R STR1.KL=AUX4.K*AUX5.K*CON5*.3
C CON5=.9
R STRM.KL=Q4.K*CON6
C CON6=.33
A COST.K=DIST.K+FIX.K+SUBS.K
L Q11.K=Q11.J+DT*(Q1.J)
L Q22.K=Q22.J+DT*(Q2.J)
L Q33.K=Q33.J+DT*(Q3.J)
L Q44.K=Q44.J+DT*(Q4.J)
L QAG.K=QAG.J+DT*(INAG.JK-OTAG.JK)
A SU6.K=12000*3.96*.05
A SU5.K=SU2.K*SU6.K
A ENSK.K=9.3E4*SKLS.K
C END=14+E6
R OTAG.KL=QAG.K*OCON
R INAG.KL=SU5.K
A SU4.K=SU5.K*SU3.K
A SU2.K=.19*SU1.K
A SU3.K=SU1.K-SU2.K
C ACON=35E-6
A SU1.K=ACON*AUX5.K
A SU5.K=4057*500*4.5*3.95*.05
T PTB=42E4/45E4/49E4/48E4/52E/52E4/
A POP.K=TABLE(PTB,TIME.K,0,30,5)
T AGTB=3000/7800/7500/8300/8000/5700/300
A AGRI.K=TABLE(AGTB,TIME.K,0,30,5)
T CTAB=1000/1000/1000/1200/1600/1800/1900
A COAL.K=TABLE(CTAB,TIME.K,0,30,5)
T BGTB=46/84/137/257/527
A FX.K=3.4E4*END
A BG.K=TABLE(BGTB,TIME.K,0,30,5)
T LTAB=590/1300/3473/14314/44027
A LOPE.K=TABLE(LTAB,TIME.K,0,30,5)
T DTAB=700/2000/6370/17061/51359/
A DEER.K=TABLE(DTAB,TIME.K,0,30,5)
```

```
A SKAX.K=TABLE (SKTB,TIME.K,[illegible])
R INSK.KL=SKAX.K
L SKLS.K=SKLS.J+DT*(INSK.JK)
A ENST.K=GSTR.K*1[illegible]
R INST.KL=.11*AUX5.K
L GSTR.K=GSTR.J+DT*(INST.JK)
C GCON=1
A DIST.K=U1.K+U2.K+U3.K+U4.K
A FIX.K=1E12
A SUBS.K=2.1E7*224*3.96*.05
A RDY3.K=(1+.6/91)*AUX5.K
L RDY1.K=RDY1.J+DT*(RDY2.JK)
R RDY2.KL=RDY3.K
A REV3.K=(7/109)*AUX5.K
L REV1.K=REV1.J+DT*(REV2.JK)
R REV2.KL=REV3.K
A AUXM.K=(2.8E10/9.2E6)*AUX5.K
R CUSM.KL=AUXM.K
L MIN.K=MIN.J+DT*(CUSM.JK)
A AUXR.K=(2E10/500000)*AUX5.K
R RR2.KL=AUXR.K
L RR.K=RR.J+DT*(RR2.JK)
A RR1.K=1.8E10+((1.69E10/500000)*35226)
L CRES.K=CRES.J+DT*(-CUM.JK)
N CRES=85.4E9
L M1.K=M1.J+DT*(RDY2.JK+REV2.JK-INSK.JK-INST.JK)
L ENSR.K=ENSR.J+DT*(SKLS.J+GSTR.J)
R CUM.KL=AUX5.K
L CCUM.K=CCUM.J+DT*(CUM.JK)
L GGAG.K=GGAG.J+DT*(GAG.J)
A SUM.K=U1.K+U2.K+U3.K+U4.K+GAG.K+EST.K+ESK.K+

TIME SUBSCRIPT SHOULD BE.JK
                        V
A      [illegible].K+CUSM.K+ACRE.K

TIME SUBSCRIPT SHOULD BE.K
                     V
A  STO.K=AUX5*10000*2000
                    R ACR.KL=ACRE.K
                    L AC.K=AC.J+DT*(ACR.JK)
                    R STR.KL=STO.K
                    A SR.K=SKLS.K+DSTR.K
                    L ST.K=ST.J+DT(STR.JK)
                    A VY.K=REV1.K+RDY1.K
                    A ACRE.K=AUX5.K*35E-6*1500*160
                    A ESK.K=[illegible]*SKAX.K
                    A RRR.K=((1.69E10/500000)*35226)+AUX?.K+1.8E10
                    A TOT.K=U11.K+U22.K+U33.K+U44.K+GGAG.K+RR.K+MIN.K+ENSR.K
                    A EST.K=.11*AUX5.K*152601
                    N M1=1
                    N ENSR=1
                    N GAG=1
                    N RR=1
                    N MIN=1
                    N REV1=1
                    N RDY1=1

PAGE 3          NGP MODEL       5/23/76

                    N GSTR=1
                    N SKLS=1
                    N U22=1
                    N U11=1
                    N U33=1
                    N U44=1
                    N GGAG=1
                    N U1=1
                    N U2=1
                    N U3=1
                    N U4=1
                    N P=2E13
                    PLOT RR=R,MIN=M
                    PLOT RT=[illegible]
                    PLOT [illegible]
                    PLOT VY=V,[illegible]
                    PLOT [illegible]
                    PLOT [illegible]
                    PLOT [illegible]
                    PRINT [illegible]
                    PRINT [illegible]
                    SPEC [illegible]
```

```
                 T SKTB=2E6/3E6/2E6/1.5E6/5E6/4E6/5E6/
                 A SKAX.K=TABLE(SKTB,TIME.K,0,30,5)
                 R INSK.KL=SKAX.K
                 L SKLS.K=SKLS.J+DT*(INSK.JK)
                 A ENST.K=QSTR.K*132531
                 R INST.KL=.11*AUX5.K
                 L QSTR.K=QSTR.J+DT*(INST.JK)
                 C QCON=1
                 A DIST.K=Q1.K+Q2.K+Q3.K+Q4.K
                 A FIX.K=1E12
                 A SUBS.K=2.1E7*2E4*3.96*.05
                 A RDY3.K=(14.6/91)*AUX5.K
                 L RDY1.K=RDY1.J+DT*(RDY2.JK)
                 R RDY2.KL=RDY3.K
                 A REV3.K=(47/109)*AUX5.K
                 L REV1.K=REV1.J+DT*(REV2.JK)
                 R REV2.KL=REV3.K
                 A AUXM.K=(2.8E10/9.2E6)*AUX5.K
                 R CUSM.KL=AUXM.K
                 L MIN.K=MIN.J+DT*(CUSM.JK)
                 A AUXR.K=(22E10/500000)*AUX5.K
                 R RR2.KL=AUXR.K
                 L RR.K=RR.J+DT*(RR2.JK)
                 A RR1.K=1.8E10+((1.69E10/500000)*352E6)
                 L CRES.K=CRES.J+DT*(-CUM.JK)
                 N CRES=85.2E9
                 L MI.K=MI.J+DT*(RDY2.JK+REV2.JK-INSK.JK-INST.JK)
                 L ENSR.K=ENSR.J+DT*(SKLS.J+QSTR.J)
                 R CUM.KL=AUX5.K
                 L CCUM.K=CCUM.J+DT*(CUM.JK)
                 L QGAS.K=QGAS.J+DT*(QAG.J)
                 A SUM.K=Q1.K+Q2.K+Q3.K+Q4.K+QAG.K+EST.K+ESK.K+

TIME SUBSCRIPT SHOULD BE.JK
               V
A    RRR.K+CUSM.K+ACRE.K

TIME SUBSCRIPT SHOULD BE.K
          V
A  BTU.K=AUX5*10000*2000
                 R ACR.KL=ACRE.K
                 L AC.K=AC.J+DT*(ACR.JK)
                 R BTR.KL=BTU.K
                 A SR.K=SKLS.K+QSTR.K
                 L BT.K=BT.J+DT(BTR.JK)
                 A VY.K=REV1.K+RDY1.K
                 A ACRE.K=AUX5.K*352E6*1500*125
                 A ESK.K=0.034*SKAX.K
                 A RRR.K=((1.69E10/500000)*352E6)+AUX7.K+1.8E10
                 A TOT.K=Q11.K+Q22.K+Q33.K+Q44.K+QGAG.K+RR.K+MIN.K+ENSR.K .
                 A EST.K=.11*AUX5.K*132631
                 N MI=1
                 N ENSR=1
                 N GAG=1
                 N RR=1
                 N MIN=1
                 N REV1=1
                 N RDY1=1
```

```
PAGE 3        NGP MODEL        5/23/76
              N QSTR=1
              N SKLS=1
              N Q22=1
              N Q11=1
              N Q33=1
              N Q44=1
              N QQAG=1
              N Q1=1
              N Q2=1
              N Q3=1
              N Q4=1
              N P=2E13
              PLOT RR=R,MIN=M
              PLOT BT=A
              PLOT ENSR/AC
              PLOT VY=V,SR=5
              PLOT DEER=D,LOPE=L,QQ=G
              PLOT TOT=T,BT=B
              PLOT TOT=T/BT=B
              PRINT TOT
              PRINT Q11,Q22,Q33,Q44,QQAG,RR,MIN,BT,ENSR,VY,SR,
              SPEC DT=.5/LENGTH=60/PRTPER=2/PLTPER=.5
```

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